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KEY PARAMETERS AND FORM-FINDING OF AN INNOVATIVE PREFABRICATED STEEL BRIDGE

Pei Chi[1], Zhebin Dai[2], Jun Dong[3]✉

Institute of Steel Structures, Nanjing Tech University, No. 30 Puzhu Road(s), 211816 Nanjing, China
E-mails: [1] chipei@njtech.edu.cn; [2] daizhebin@njtech.edu.cn; [3] dongjun@njtech.edu.cn

Abstract. Accelerated bridge construction is desired in urban areas or after natural disasters, thus, it has drawn the attention of the bridge community and transportation agencies worldwide. It has lead to the advancement of accelerated construction techniques using prefabricated bridge elements. In this paper, an innovative self-balanced bridge structure consisting of assembly truss units, flexible cables, and struts is proposed. All components of this truss string structure are fabricated in the precast plant before being shipped to the construction site, therefore reducing the amount of labor and time on-site significantly. The mechanical performance of this structure is studied with three-dimensional finite-element method under the influence of key parameters such as the number of struts, the distance between struts, sag-span ratio, and initial pretension. Parametric analysis of 6 pedestrian bridge models with typical span shows that the optimized structure form reduces steel consumption by up to 59.4% compared to regular truss structures.

Keywords: bridges, prefabricated bridge, accelerated bridge construction, truss string structure, parametric analysis, form-finding.

1. Introduction

Accelerated bridge construction (ABC) in urban areas has recently been a subject received much attention from the bridge community and transportation agencies, as a way of alleviating traffic congestion (Hällmark *et al.* 2012; Leshko 2006; Schexnayder, Anderson 2010). The speed of transportation construction, particularly in case of transforming an existing roadway, has become a critical issue for the sake of minimizing disturbances to the traffic flow, and business loss, and ensuring work-zone safety (Li, Ma 2010). If all the components of the bridge are fabricated in the precast plant under closely monitored conditions, shipped to the construction site, and quickly assembled together, then the amount of labor and time on-site are able to be reduced significantly, meanwhile minimizing the negative impact on the traffic and the environment in the vicinity of the site (Alizadeh *et al.* 2014; Shah *et al.* 2007). Moreover, accelerated bridge construction is essential for the success of disaster relief efforts, as these structures provide access routes to restore vital lifelines for the affected communities after natural disasters (Russell, Thrall 2013). China is among the countries that saw most natural disasters. Various kinds of disasters that took place in China such as the Wenchuan earthquake in 2008 and the Zhouqu mudslide in 2010, often cause severe damages (Sun *et al.* 2012).

In recent decades, research on prefabricated steel bridge has been carried out worldwide, and the most famous one is the Bailey Bridge (Connors, Foss 2011) invented by Sir Donald Bailey as a military bridge in 1940. Subsequently, a series of prefabricated bridge elements and systems (PBES), such as the Medium Girder Bridge (MGB), Acrow Bridge, and Mabey Logistic Support Bridge (Russell, Thrall 2013) have taken advantage of modern developments in bridge design and steel technology to enhance their bearing capacity and improve their durability and the reliability. In this paper, an innovative ABC structure is proposed, which is a self-balanced system composed of assembly trusses units, flexible cables, and struts shown in Fig. 1. The assembly truss unit is made by joining standard triangle truss units, end triangle truss units, and struts with steel pins. Details about the members of assembly truss units are shown in Fig. 2. All components of the structure are fabricated in the precast plant before being shipped to the construction site. They are light-weighted, easy to be assembled rapidly into a bridge structure satisfying the strength, stiffness, and stability requirements.

This innovative prefabricated truss string structure for accelerated pedestrian bridge construction is realized by introducing lower-chord cables into the China Type 64 military girder. These cables are reinforced by pretension in a way to fully utilize the tensile capacity of high-strength steel, thus reducing the weight and improving the static performance of the structure. The pretension resulted from structure deformation acts on the truss as

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an external load, making the entire structure into a self-balanced system. Due to the pretension in the cable, the lower chords are in compression, the upper chords are in tension, and the diagonal web members are in compression alternated with tension, leading to negative deflection in the truss structure. Under vertical load, the axial force in the lower chords is changed from compression to tension, and the tension in the cable is further increased.

2. Modeling and load

To quantitatively analyze the structure parameters of this truss string structure (TSS), an urban pedestrian bridge with typical span on a trunk road is examined. The urban trunk road has medial strip and carries four lanes of motor traffic on each side, the typical span $L = 1.5 + 0.25 + 3.5 \cdot 4 + 0.25 + 2.5 = 18.5$ m. Select 4 m as the modulus of the TSS, then the span is 20 m. As the regulations for pedestrian traffic in commercial districts demands the highest standard, with the shortest side pavement width of 4.0–5.0 m, the side pavement width is chosen to be 4 m, which is also the maximum spacing between two truss string structure frames.

Truss members sizing is chosen as follows: steel channel C160×60×20×3.0 for both the lower and upper chords; C80×40×15×2.5 for diagonal and end web members; steel angel *L*30×2 for middle web members; *L*20×2 for subdivided web members; steel circular hollow section Ø70×2 for struts; and high strength steel strands (yield stress 1570 MPa) φ5×37 for cables.

Gravity loads on the steel bridge deck system are determined as follows: bridge deck, 0.94 kN/m^2; the vertical beam, 0.47 kN/m^2; the lateral beam, 0.42 kN/m^2; deck system, 2 kN/m^2 (the weight of connecting components is taken into account); pedestrian load, 4 kN/m^2. In the calculation of bearing capacity, external load is the combination of 1.2 times gravity loads plus 1.4 times live load plus the pretension in the cable, while nominal values of the loads are used for computing deformation.

3. Effects of strut number and space between struts

The vertical struts provide elastic support to the rigid superstructure. The number of struts needs to be optimized, as too many struts would increase material consumption and also complicate construction; less than appropriate number of struts, however, would not effectively decrease the internal forces and the displacement induced in the structure, therefore deteriorating its overall performance (Misiunaite *et al.* 2012).

For even numbers of struts, the relation between the mid-span deflection and the space between struts under cable force and pedestrian load is shown in Fig. 3a and the relation between the axial force ratio and the space between struts in Fig. 3b, respectively. Both figures indicate a nonlinear variation with the distance between struts. With the increase of the space between struts (the number of struts is decreased consequently) the mid-span deflection is increased, the axial force ratios of the struts and lower chords at the mid-span location are also increased, but the axial force ratios of the upper chords at the mid-span location and the mid-span cable remain roughly unchanged. In general, when the space between struts is less than 4 m, the mid-span deflection and axial force ratio of all truss members except for struts change mildly.

For odd numbers of struts, the relation between the mid-span deflection and the space between struts is shown in Fig. 4a and the relation between the axial force ratio and the space between struts in Fig. 4b, respectively. Fig. 4a suggests an increase in the mid-span deflection with larger

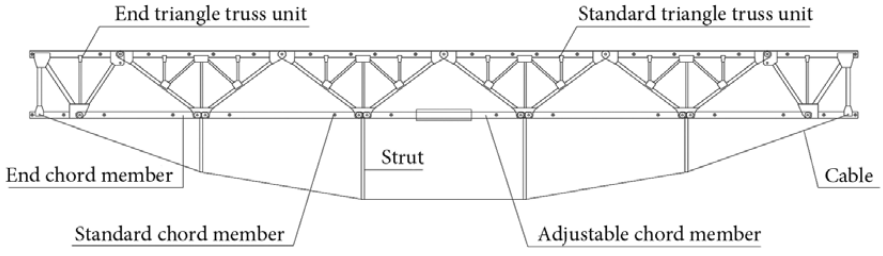

Fig. 1. Major components of the TSS (truss string structure)

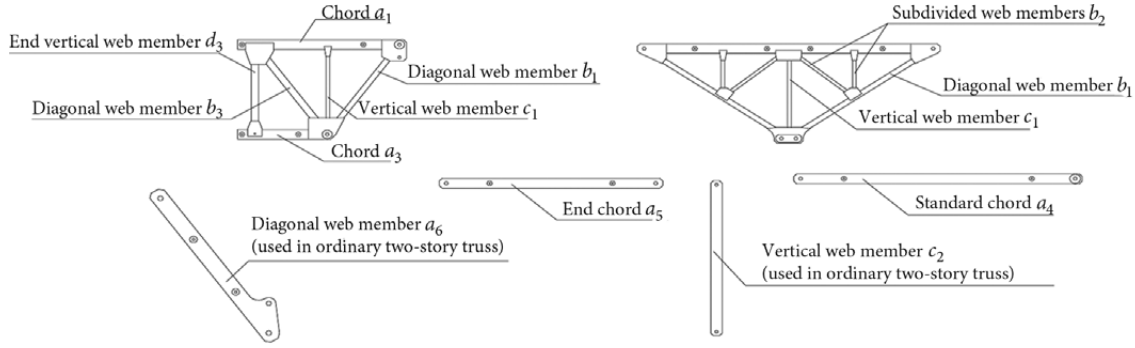

Fig. 2. Components of the assembly truss unit

space between struts. Fig. 4b shows that the axial force ratio of all truss members except for the struts remain relatively constant. In conclusion, the number of struts has a significant effect on the mid-span deflection, but not on the axial force in the truss members except for the struts themselves.

N/N_0 in Fig. 3 and Fig. 4 represent the axial force ratio of members, with N_0 representing the axial force in members when the space between struts is 1 m and struts number is 19.

4. Effect of the length of strut/sag-span ratio

Sag-span ratio is an important variable in studying truss string structures, as it has a significant impact on the internal forces and displacements of the truss members, and also on steel consumption. It is also a key index for the shape of the structure (Kalanta *et al.* 2012).

Sag-span ratio is proportional to the length of the struts. Increasing the strut length (which would increase the sag-span ratio) would decrease the mid-span deflection (Fig. 5a). For strut lengths greater than 3 m, or sag-span ratio larger than 0.15, the deflection varies little. The change of the axial force ratio of each truss member with the length of strut is shown in Fig. 5b.

5. Effect of initial pretension

Pretension is introduced in the cable in order to obtain adequate amount of integral rigidity in the entire structure

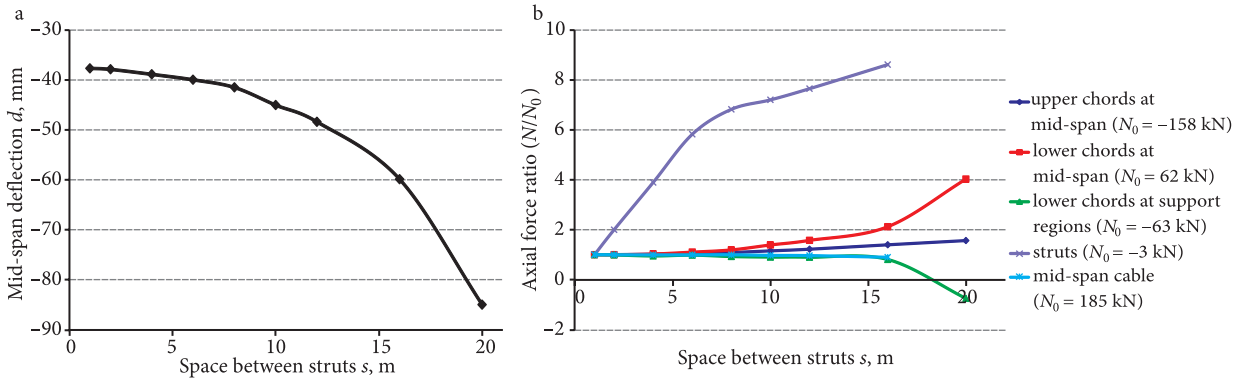

Fig. 3. Variation of mid-span deflection and axial force ratio with space between struts (when struts number is even): a – mid-span deflection versus the space between struts; b – axial force ratio versus the space between struts

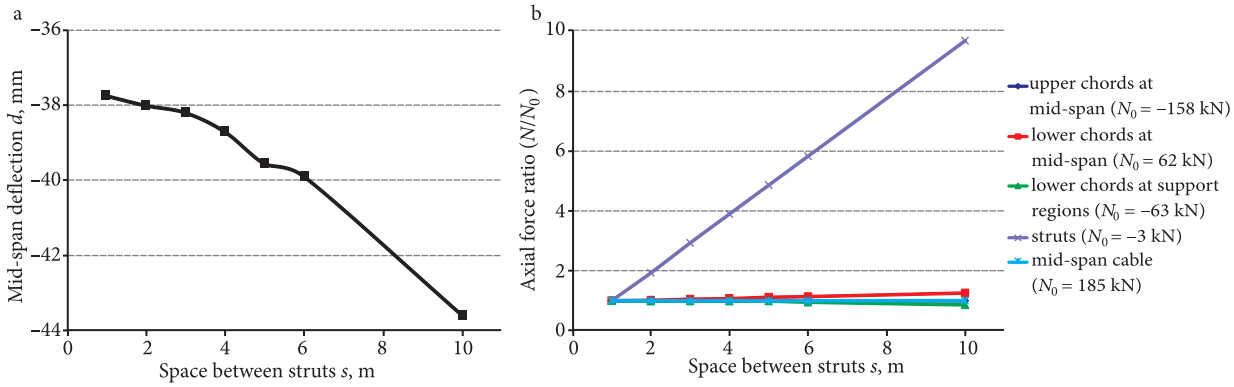

Fig. 4. Variation of mid-span deflection and axial force ratio with space between struts (when struts number is odd): a – mid-span deflection versus the space between struts; b – axial force ratio versus the space between struts

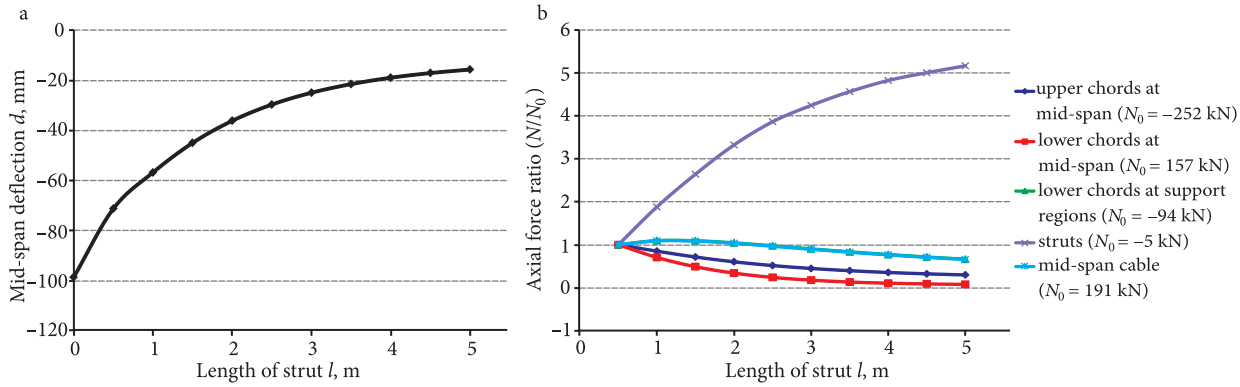

Fig. 5. Variation of mid-span deflection and axial force ratio with the length of strut: a – mid-span deflection versus the length of strut; b – axial force ratio versus the length of strut

and ideal geometrical configuration. The magnitude of pretension is critical to the mechanical performance of the structure (Sandovic, Juozapaitis 2012). Overly large magnitude would increase the axial force in the truss members and increase steel consumption; while less than enough magnitude would lead to structural failure resulting from cable slacking.

According to the formula proposed by (Liu 2001) the equivalent uniformly distributed load q_{eq} is:

$$q_{eq} = \frac{8H_0(f_1 + f_2)}{l^2}, \quad (1)$$

where H_0 – the initial pretension, kN; f_1 – the rise of the superstructure, m; f_2 – the rise of the string, m; l – the structure span, m.

The ratio of the equivalent uniformly distributed load to gravity load, K, is:

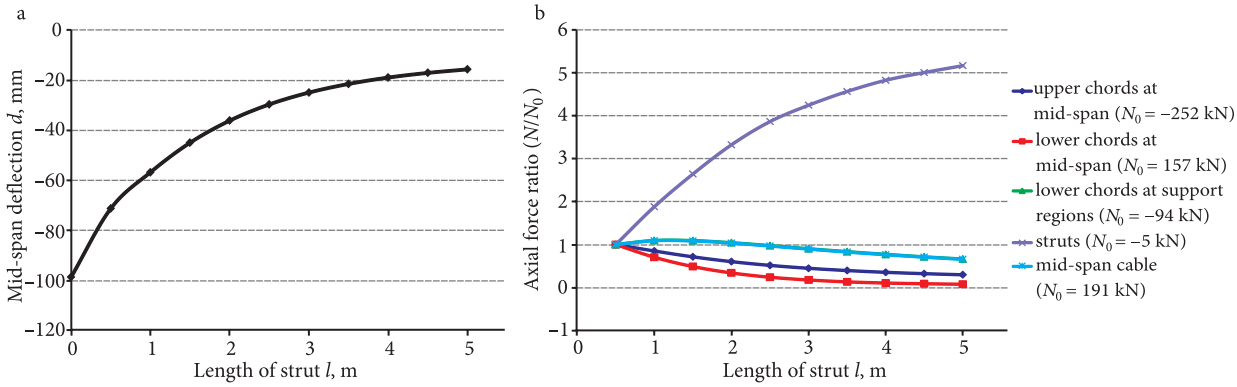

Fig. 6. Variation of mid-span deflection and axial force ratio with the value of K: a – mid-span deflection versus the value of K; b – axial force ratio versus the value of K

Table 1. Comparison of different models

Model number	Sag-span ratio	Pretension, kN	Mid-span deflection, mm	Max-compressive stress, N/mm^2	Max-tensile stress, N/mm^2	Steel consumption, t	Save, %
MODEL 0	0	0	–10.96	–267	296	2.56	–
MODEL 1	0.05	205	–24.78	–270	296	1.58	38.3
MODEL 2	0.075	133	–24.92	–268	298	1.26	50.8
MODEL 3	0.1	105	–24.84	–274	287	1.04	59.4
MODEL 4	0.125	60	–24.92	–269	264	1.06	58.6
MODEL 5	0.15	22	–24.97	–274	290	1.09	57.4

Table 2. Section dimensions of different models

Member	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5
a_1	C250×50×4.0	C250×50×4.0	C250×50×4.0	C220×75×25×3.0	C220×75×25×3.0	C200×60×20×3.0
b_1	C160×70×20×3.0	C120×50×20×2.5	C100×50×15×2.5	C80×40×15×2.5	C80×40×15×2.5	C80×40×15×2.5
c_1	L50×3	L50×3	L50×3	L50×3	L50×3	L50×3
b_2	L20×2	L20×2	L20×2	L20×2	L20×2	L20×2
d_3	C250×50×4.0	C140×60×20×3.0	C120×60×20×3.0	C120×50×20×2.5	C100×50×15×2.5	C100×50×15×2.5
b_3	C220×75×25×3.0	C120×50×20×2.5	C100×50×15×2.5	C80×40×15×2.5	C80×40×15×2.5	C80×40×15×2.5
a_3	C250×50×4.0	C250×50×4.0	C250×50×4.0	C220×75×25×3.0	C220×75×25×3.0	C200×60×20×3.0
a_4	–	C120×60×20×3.0	C100×50×15×2.5	C80×40×15×2.0	C80×40×15×2.0	C80×40×15×2.0
a_5	–	C140×50×20×2.0	C140×50×20×2.0	C140×50×20×2.0	C140×50×20×2.0	C140×50×20×2.0
a_6	C220×75×25×3.0	–	–	–	–	–
c_2	C160×70×20×3.0	–	–	–	–	–
strut	–	Ø40×2	Ø51×2	Ø60×2	Ø76×2	Ø102×3
cable	–	φ5×37	φ5×37	φ5×37	φ5×37	φ5×37

$$K = \frac{q_{eq}}{q_0}, \quad (2)$$

where q_0 – the gravity load, kN/m.

Variations of the mid-span deflection and axial force ratio of truss members with K are shown in Fig. 6. With the increase of K, the mid-span deflection (Fig. 6a) and the axial forces ratio (Fig. 6b) in the upper and lower chords at the mid-span location decrease linearly; while the axial force ratios in the lower chords in the support region, struts and mid-span cable increase slightly.

N/N_0 in Fig. 5 and Fig. 6 represent the axial force ratio of members. N_0 in Fig. 5 represents the axial force in members when the length of the strut is 0.5 m, sag-span ratio is 0.025; in Fig. 6 it represents the axial force in members when the initial pretension is 10 kN.

6. Form-finding

6.1. Design requirements

The maximum vertical deflection caused by pedestrian load is limited to $L/800$ = 25 mm; the 3 Hz vertical vibration frequency corresponds to the limit specified for the upper structure of the bridge in *CJJ 69-95 Technical Specifications of Urban Pedestrian Overcrossing and Underpass*. According to *GB 50018-2002 Technical Code of Cold-Formed Thin-Wall Steel Structures*, the requirement for the axially loaded compressive members is:

$$\varphi f \le \frac{N}{A_e}, \quad (3)$$

where φ – the stability coefficient; f – the design value of strength, MPa; φf – the buckling strength, MPa; N – the buckling resistance, N; A_e – the effective sectional area, mm^2.

For compressive diagonal web members, $\varphi f = 0.909 \cdot 300 = 272.7$ MPa; for compressve chords, $\varphi f = 0.913 \cdot 300 = 273.9$ MPa; for compressive vertical web members, $\varphi f = 0.838 \cdot 300 = 251.4$ MPa. The maximum stress allowed in tension members is 300 MPa.

According to the literature (Jiang, Wang 2007), the safety factor of the cable is in the range of 2.5 to 3.0, and 3.0 is selected in this paper.

6.2. Model analysis and results

Analysis results of the key parameters introduced in the previous sections show that sag-span ratio is the most significant factor on the mechanical performance of the TSS. Pretension in the cable is also essential to establish the structure, and the number of struts only determines the internal forces in themselves.

Sag-span ratio is therefore taken as a control variable, based on which the pretension in the cable and the cross-sectional sizing are adjusted, thus 5 new TSS models are created, ensuring that the mid-span deflection and the maximum composite stress of each model are consistent with a regular two-story truss structure with the same span (MODEL 0). Table 1 lists the parameters and analysis results of each model, which indicates that MODEL 3 saves 59.4% of steel consumption compared with MODEL 0, standing out as the most economical and optimum form. Sectional dimensions of each model are also shown in Table 2.

7. Conclusions

1. The number of struts directly affects their own internal forces, but has little impact on the rest members of truss string structure. However, increasing the number of struts adequately helps to control the mid-span deflection, demonstrating its function as an elastic support to the superstructure.

2. Sag-span ratio has great effect on the structure performance: increasing this ratio would decrease the mid-span deflection significantly and the internal forces in the members tend to decrease except for the struts. Only when it exceeds a certain value, further increasing would not improve the structural performance.

3. The pretension influences the mid-span deflection and axial force in a linear way. An increase in the pretension would decrease the mid-span deflection and improve the mechanical performance of the chords. However, excessive pretension would impose an adverse impact on the stability of the chords by increasing the internal force. Therefore the magnitude of the pretension has to be calculated carefully from given conditions such as the magnitude of loads, stiffness of members, et al.

4. For a pedestrian bridge with typical span of 20 m, the optimum structural form with 4 struts spaced 4 m in between, sag-span ratio of 0.1, and initial pretension of 105 kN, is able to save 59.4% of steel consumption compared with regular truss structure.

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