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Experimental study on the cable rigidness and static behaviors of AERORail structure

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Abstract. This paper presented a new aerial platform-AERORail for rail transport and its structure evolution based on the elastic stiffness of cable; through the analysis on the cable properties when the cable supported a small service load with high-tensile force, summarized the theoretical basis of the AERORail structure and the corresponding simplified analysis model. There were 60 groups of experiments for a single naked cable model under different tensile forces and different services loads, and 48 groups of experiments for the cable with rail combined structure model. The experimental results of deflection characteristics were compared with the theoretical values for these two types of structures under the same conditions. It proved that the results almost met the classical cable theory. The reason is that a small deflection was required when this structure was applied. After the tension increments tests with moving load, it is verified that the relationships between the structure stiffness and tension force and service load are simple. Before further research and applications are made, these results are necessary for the determination of the reasonable and economic tensile force, allowable service load for the special span length for this new platform.

Keywords: cable stiffness; static behaviors; tension force; service load; classical cable theory; deflection; tension increment

1. Introduction

With the arrival of peak period of passengers and freight trains, high-speed rail and urban rail transportation, more and more transportation systems and structure platforms are emerging, including unconventional, new-style and complex systems. Most of these new means of transportation are energy-saving, economic, efficient and environmental friendly. Considering the technological development and social progress, the current world pays more attention to the low-carbon technology and environmental protection requirements, and therefore some smart, novel and untraditional ideas, even the whimsical ideas about an alternative transportation system, have been accepted gradually, and some have been put into practice as entertainment facilities.

In the web of University of Washington, there is a compendium of next-generation transportation alternatives including more than 100 types of innovative transportation program (Jerry and Rich 2011). They have been grouped into different categories according to the vehicles' position, including the ones supported by an elevated guideway and suspended by an elevated guideway. In view to the guideway,

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more than 3/4 structures are based on rails as their transport platform. The reason is that the designers are aware of the limitations of ground transportation. In order to achieve the rail, basic research on the track structure is necessary. Considering those rail structures, nearly a half types of structures are light track structures, which cannot succeed if they are without the cable supports. As typical examples related to this paper, several track's structures of the transport platforms are discussed below to help readers to understand the object and purpose of this paper.

A bike platform, invented by Kolelinia Company (Angelov 2011), was reported recently. It's an absolute cable structure as the platform, with a U-shaped groove for the bicycle tire. The cables cannot be displaced by other structural alternatives for its economy to support the light service load. The basic principle of this structure is supported by the bottom U-shaped groove to bear all loads passed through the bicycle tire in the vertical direction, while taking advantage of the one upper cable to hold the bicycle to avoid the bicycle overturning in the transverse direction. The similar guideways includes Aerobus system (Jerry and Rich 2011) and String Transport System (Jerry and Rich 2011), etc.

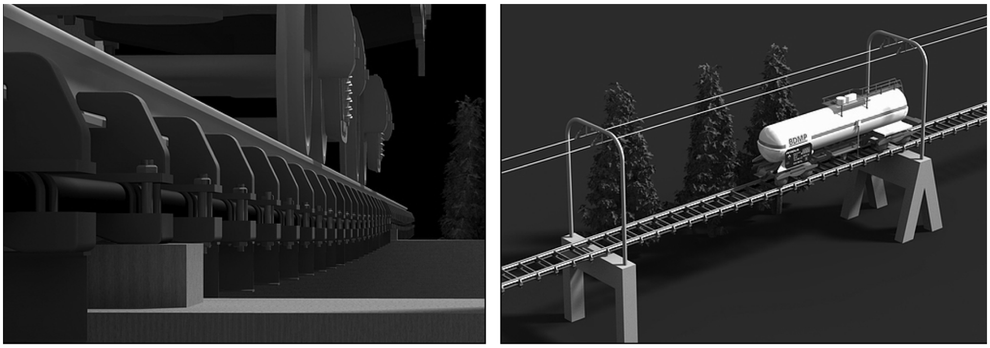
Although some transport platforms use steel beam completely, but if they are combined with the cable support, the platforms structure will be more economical. There are many different kinds of tracks for entertainment in the parks, which completely use steel beam as their support platforms. For another example, the SHWEEB System uses the steel track to suspend the vehicle cells. Its standard span is about 20 m (Barnett 2010). If it combines the cable structure, it will be beneficial to increase the span and greatly reduce its cost. The platform discussed in this paper does not include the use of the suspension or cable-stayed bridge to increase the span of the platform. A similar transport platform reported recently is the Skytran system (Jerry and Rich 2011).

In fact, most of these conceptual designs will use the cable to increase their mechanical reliability, stability and security. The object of this paper - a new aerial track structure (named AERORail), is evolved and developed from the above ideas. The basic mechanical characteristics of the AERORail will be analyzed for its pre-tensioned cable structures. The corresponding model tests will be carried out. As a new structure, the introduction for the AERORail structure is necessary.

2. AERORail Structure

AERORail structure may be called a new bridge structure for its transportation function. It is a platform without any steel beams or concrete beams as bridges to support the vehicles. The pre-tensioned cables directly support the upper tracks as rails, which allow the vehicles to run along them at high speed (Li *et al*. 2010, Li *et al*. 2011). The computer-rendering pictures are shown in Fig.1. The main members of this structure are pre-tensioned cables. It is well known that the cables' bending stiffness is very small, so the lateral service loads on the cables mainly withstand by the axial stiffness. If a greater axial pre-tension force is imposed to reduce the lateral deflection to a certain extent, the purpose of smooth traffic platform can be achieved. For a certain span with an enough large pre-tension force, the static deflection of this structure can be very small, but still closely associated with the amount of lateral load.

The main characteristic of the AERORail structure is that it can achieve allowable deflection under the possible maximum cable tension with a certain economic and reasonable span, and with corresponding service load. Due to the soft and small damp features of the cable track structure, when it serves for the moving vehicle loads, the dynamic coupling characteristics become more pronounced. It is essential to study the characteristics of this structure under the vehicle load forces to determine the



(a) Local drawing of small span assemble system (b) Assembled system with vehicle

Fig. 1 AERORail rendering pictures

structure's safety, economy and reliability for its application in the future.

The new AERORail platform has more merits, including its light structure and fewer construction works, high construction speed and short construction time, low investment and high transport efficiency, low energy consumption and less pollution, less restricted by topography and climate, etc. It fits the same direction with developing trends of current traffic engineering and bridge engineering. Development of this kind of transportation can reduce the traffic resource constraints, and satisfy the current energy, environmental protection concepts, which can get high economic value and social benefits, especially meet the requirement of China's current transportation states.

2.1 Cable structure for bridge and its theoretical basis

There are many types of cable structure bridges. The first ancient rope bridge is made of bamboo or rattan, whose structure forms are still applied nowadays. The recorded world's first suspension bridge is a bamboo bridge in Yizhou, Sichuan, China (now Chengdu, built in the Qin Dynasty (B.C. 251) and has been 2260 years up to present. The iron chain suspension bridges date from A.D. 65, which was built in Yunnan, China (Wang 2007). Due to the low strength of rattan or early iron, they were always used as the suspender member. Although these types of bridges are still in use under certain condition, as the cable structure bridges, the suspension bridge and cable-stayed bridge are the two important types in the modern bridge engineering.

In 1970, inventor Gerhard Mueller developed a similar structure as the suspension bridge with an elevated cable structure for the vehicle system (Shen *et al*. 2004). This system consists of double-layer cables, similar to the main cable of a suspension bridge, on which a greater pre-tension force was imposed, so that the vehicle with power can hang and run on them and cross long span. Because this system with a cable structure has a greater rigidity, the vehicle can run fast at the speed up to 80 km/h. The vehicle as the train, with a larger load capacity, can cross the barrier in the city (such as heavy traffic routes, rivers and buildings, etc.) to build a new traffic mode of transport, and it is named Airbus system. This system in the past 30 years in Switzerland, Canada, Germany and other countries has been built for trial line or for operation. In particular, it is well known as the second-generation Germany Mannheim Airbus system, which solved the public transport problems for the International Horticultural Mannheim Expo in 1975. The Transportation Department of USA has conducted a comprehensive inspection and full evaluation for this system, and made a number of improvements.

After several years of development, this technology is more mature now (Shen *et al*. 2004, Jerry and Rich 2011).

The hung cable structure for Airbus system as the load-bearing structure for the transport system is a flexible double cable net. The key prototype structures for long span are very similar to a suspension bridge, but the lower part of the platform is still a cable mounting structure, and need to take advantage of the structure stiffness. Because the whole structure is affected by double-cable structure, the geometric nonlinear deformation is serious under external loads. To solve this problem, we must consider the initial state and non-linear performance of the structure.

In recent years, some countries are researching on the application of the stressed ribbon bridge (also named stress-ribbon bridge). For example, in the Technical University of Brno, Czech, the stress ribbon and cable supporting pedestrian bridges have been studied in different structural forms. Such bridges are typically made from concrete reinforced by steel tensioning cables. The characteristic of a stressed ribbon bridge is a tension structure (similar in many ways to a simple suspension bridge). The suspension cables are embedded in the deck, which follows a catenary shape between supports (Jiri 2005, 2010).

In fact, this kind of bridge is not used recently. It has been more like the military cable bridge, which are always applied and studied for rapid construction and military purposes. This structure regains vitality due to the development of high-strength cable and precast assembly construction technology. However, limited by their dynamic behavior, the service load is always subject to a certain restriction, and they are always applied to the bridges for pedestrians, bicyclists, and pipelines and so on.

To change this limitation, the ribbon is stressed in compression, which adds the stiffness of the structure. The stiffness is always obtained by stressing the concrete in compression. The supports in turn support upward thrusting arcs that allow the grade to be changed between spans for multiple-spans structure. A certain degree of stiffness is required to prevent excessive flexure of the bridge for service load, but it is difficult. That is why it is always used for pedestrians or bicyclists.

Using the ultra-high tensile properties and the characteristics of cable tension structure, the researchers also created many unique structures of the new bridge, such as the inverted arch bridge with pre-tensioned cable designed by the Flexible Structure Research Institute of Kunming Technology University, Yunnan, China (Liu and Qu 1994). This structure uses the pre-tensioned cable and rod to get the stiffness for a bridge. Its main feature is, when the vehicle moving on it, the vertical and horizontal deformation of the bridge is very small. It can be used in various temporary construction bridge, sightseeing bridges, and highway bridges for its attractive appearance.

The inverted arch cable bridges and stressed ribbon bridge are put into practice increasingly. It indicates that the technology of cable structure bridges is still developing and improving, because carrying capacity of these bridges can be increased dramatically and the application ranges can be widened. Meanwhile, researchers are still striving in a easier way to achieve structural stiffness to upgrade the platform for vehicles (Li *et al*. 2010).

Since mid-1970s, Russian inventor Anatoly Yunitsky has been studying a String Transport Yunitsky system (ever named STU, UST and STS) (Unitsky 2004). It is proposed for both freight and passengers and received grants from United Nations Human Settlements Programmer. This elevated system is based on the use of strings built with high-tensioned steel wires inserted into a concrete or resin core and enveloped within a steel shell. It differs from traditional cable ropeways. Short span coupled with high-tension force, STU is better than common ropeway as a light structure for its high stiffness. This structure allows low sag for running vehicle at high speed (Unitsky 2005). It is a pity that there is no STU system in service nowadays, but only a 150m test model was set up.

Although STU and AERORail are all guideway supported by cables, they differ from the rattan rope bridge and suspension bridge in their high stiffness. Moreover, the lateral loads on the cable are small, which is similar to the cable properties of the cable-stayed bridge in some degree. Because the cable of a cable-stayed bridge is usually longer than that of the STU or AERORail between two supports, the behaviors of the pre-tensioned cables are relatively different. Therefore, if the tension force in the main cable of the rope bridge is large enough, its behaviors will be close to the pre-tensioned cable structure. When the main cables for the inverted arch bridge bear large vertical and horizontal forces, their behaviors will be similar to those of the hybrids, consisting of pre-tensioned rigid cable and suspension cable, and the stressed ribbon bridge and pre-tensioned cable bridge structure are mainly rigid cable structures.

As a pre-tensioned cable structure, AERORail has two groups of cables to support the upper rails or tracks directly for the wheels. For a long span structure, the pre-tensioned cable structure is similar to Airbus which still needs to use a secondary suspension system or stayed cable structure, or inverted arch cable bridge structure to increase the stiffness and stability of the platform. This research is not included in this paper.

After summarizing the behaviors of above cable structures, this paper divided the cables into three categories: suspension cable structure, hybrid cable structure and the rigid cable structure according to the cable characteristics in the bridge structure or track structure of the practical project. The prerequisite is that the weight load can be ignored for a certain span, or the lateral load is relatively small. The object of this paper is the small-span and rigid-cable structure and the main content of this paper is its mechanical properties under load.

Currently, there are several methods to solve the cable structure under load and its deflection, such as the catenary curve element, the parabolic curve of the two-node element, multi-node curve element, and the rod element with prestress. If it is assumed that the structure of the cable is the ideal flexible and the stress-strain relationship under tensile force is linear, according to force equilibrium and deflection compatibility conditions, the nonlinear relationship between displacement and external load can be derived in order to establish nonlinear calculation equation. Newton-Raphson iterative analysis method can be used to calculate the internal forces and deflection under the action of the living loads (Knudson 1971, Gambhir and Batchelor 1977, Jayaraman and Knudson 1981, Fried 1982, Gimsing 1997, Tanaka *et al*. 2002).

When the rises are the same and the cable tension forces are large enough, for a larger span cable structures, it is well known that using parabolic curve to calculate the structure properties is close to the actual results. In general, suspension bridge, the rise-span ratios of the main span generally are 1/9 to 1/12. However, the ratio is about 1/15 for the Airbus system to increase its stiffness. For a small span AERORail structure, because high speeds are necessary for conveying efficiency, the corresponding rise-span ratio will be limited to about 1/1000 for a small lag of the cable and rail. Correspondingly, its mechanical characteristics and its design methods must be different and need to be modified.

2.2 AERORail structure and its characteristics

The design principle of AERORail is the use of the flexible cable to get the rigid structure under the action of pre-tension force. The major feature is as follows: there is no beam as the “bone”, but directly set supports in uniform spaces over the cables; two tracks will be laid and fixed on the supports; and the rail stiffness is insufficient to control the structure stiffness, while the stiffness still depends on the main cable.

Compared with other rigid cable structures, AERORail not only has the most characteristics of other cable platforms, but also has some its own characteristics:

(a) The cables of AERORail platform are smoother than the stressed ribbon bridge for the less sag. In all cable structures, the deflection of AERORail under the controlled load is minimal.

(b) Only a small scope pre-camber need to be adjusted with the supports between the cables and the tracks in order to ensure simplicity of the structure. It is also easy to control the track's state for moving loads of vehicles.

(c) Both two tracks and two groups of cables, with the supports between track and cable, are assembled with components, which can be divided into short sections for installation and removal. Construction and maintenance are more convenient.

(d) The frame between two sides of track can effectively prevent their separation and the torsion of the trucks.

(e) The service loads should be obtained through the test and analysis for their reasonable distribution for the static and dynamic requirements.

Although the platform of AERORail system can learn from the STU structure to choose its spans, which is divided into two groups: one is a normal form (span less than 100 m); the other is double cable structure with auxiliary cables (span larger than 100m) (Unitsky 2005). However, considering the structural differences, the reasonable spans of AERORail platform can be divided into two groups too: larger and less than 60 m, which all fall into the first groups of STU. In fact, the simple and economical span is less than 60 m, and a span of over 60 m will be adopted only to meet the special terrain. The span range of this paper is smaller than 60 m.

3. Mechanical properties of cable of pre-tensioned cable structure

3.1 Typical calculation method for an aclinic cable

It is well known that only when the cable is in a vertical state, its stiffness is independent of its weight; other hanging state cables are insensitive to the tensile force for the initial sag under its own weights. After the cable is stretched to small sag and in a line state, the cable becomes more rigid for its axial stiffness increasing. The cable's axial stiffness consists of two parts. One is well-known elastic stiffness and obeys the Hooke's law. It is also named as Hooke's stiffness. Another is the gravity stiffness. It will display when the cable has enough sag. The relationship between the cable length and tensile force depends on the elastic stiffness. The elastic stiffness has noting to do with the tension, while the gravity stiffness depends largely on the cable tension (Irvine 1981, Raoof and Davies 2004, Raoof and Davies 2004).

As an example, the aclinic cable was selected here to explain the conception of axial stiffness, which is the basis for the AERORail structure. Fig. 2 shows an aclinic cable with span *l*, cable weight per unit length is *mg*, and the sag is *d*.

Assume the shape of cable is parabolic curve, the horizontal component of tension is

$$H = \frac{mgl^2}{8d} \tag{1}$$

If each end of the cable moves $\Delta l/2$ and the cable length has no change, the relationship between tension (H), span (l) and sag (d) can be derivate according to the balance of force and deflection as simplified Eq. (2). The relationship between ΔH and Δl in Eq. (2) shows that the axial stiffness mainly

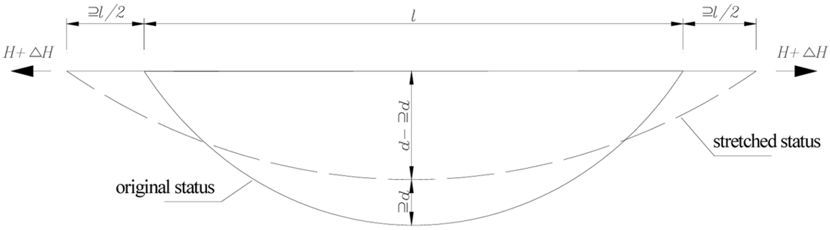


Fig. 2 Cable diagram under tension and weight

comes from gravity.

$$\Delta H = \frac{12H}{l\left(\frac{mgl}{H}\right)^2}\Delta l \tag{2}$$

According to the reference (Xiao 1997), the expression of the effective axial stiffness k_a of suspension cable is

$$K_a = \frac{1}{\frac{1}{k_g}+\frac{1}{k_h}} = \frac{k_g k_h}{k_g + k_h} \tag{3}$$

Where:

K_g - gravity stiffness, $k_g = \frac{12H}{l\left(\frac{mgl}{H}\right)^2}$

K_h - elastic stiffness, $k_h = \frac{EA}{l}$

Put K_g and K_h into Eq. (3) can get

$$k_a = \frac{k_h}{1+\frac{\lambda^2}{12}} \tag{4a}$$

or

$$k_a = \frac{k_g}{1+\frac{12}{\lambda^2}\left(\frac{H}{l}\right)} \tag{4b}$$

Where

$$\lambda^2 = \left(\frac{mgl}{H}\right)^2 \cdot \frac{EA}{l} \tag{5}$$

Here, λ^2 is a characteristic parameter for the cable. When λ^2 is very small, the denominator of Eq. (4a) tends to 1.0, K_a is almost equal to the elastic stiffness K_h. For a large sag-span ratio, corresponding to a smaller H and larger λ^2, the effective axial stiffness K_a can be replaced by the gravity stiffness K_g. The above assumptions was based on the strain of cable is small (namely H/A is small enough).

Suspension cable under the action of elastic stiffness and gravity rigidity will affect its characteristics, and have the key influence on the structure behaviors. To quantify these two effects, with a separate feature parameter λ^2 to indicate the impact by these two stiffness parameters. Under known design conditions, when λ^2 is greater than a certain value, the elastic stiffness plays a dominant role; while λ^2 is less than a certain value, the gravity stiffness plays a dominant role (Xiao 1997).

For a cable withstanding axial tensile load, such as cable for cable-stayed bridge, cable for anchor, or wind-cable for structure, the elastic stiffness plays a dominant role for the axial stiffness. For a cable withstanding a lateral load, such as cable of suspension bridge, the cable axial stiffness mainly consists of the stiffness of gravity.

The cables of AERORail structure are always in aclinic state, withstanding large axial tensile forces and lateral loads. However, relative to the cables mentioned above, which are exposed to large lateral load, the lateral load of cables of AERORail is smaller. Then the role of axial stiffness is affected by the load and sag, which is directly affected by λ^2.

Eq. (2) is one method to solve a flat cable under axial force and axial displacement, and then the corresponding stress increase can be obtained. Under the conditions of particular sag, cable axial stiffness can be resolved exactly, but the premise is the movements of two cable terminations must be very small. This application condition in theory is suitable for AERORail that the cable tension is larger with a small deflection in service stage.

In fact, according to the relationship between the cable tension and span elongation, it can be drawn for certain spans of the suspension. When the cable tension falls below a certain value, its gravity stiffness performs significantly. However, to a certain increase of the tension, the elastic stiffness will dominate the main stiffness. That is to say, from the initial loose state to tensile state, the axial stiffness of cable changes dramatically (Xiao 1997).

With the above theoretical support, in the design of AERORail structure, it is possible to achieve rapidly and determine accurately the mechanical properties of the structure. It is easy to determine the minimum service load for the allowable static deflection.

3.2 Description for cable static characteristics

3.2.1 Cable static characteristics

Considering its flexible feature, the cable is different from rod or beam, because it has a high load capacity to resist tension while very low capacity for bending. Although the cable is often applied to withstand the lateral loads with transverse deformation, but it is different from the bending beam because of its very low bending stiffness, and all the lateral load need to use the axial tension force to overcome. It is different from the tension rod too, because of the significant lateral deformation (Raoof and Davies 2004).

Cable structure is a typical geometric nonlinear structure. To bear lateral loads, it only has to adjust its curvature for its low bending stiffness. Then the structure will have a huge deflection under the action of external loads. To calculate its deflection, the balance equation should be established according to the deformed position, not based on the original location before undertaking the force. However, the deformed position is unknown. This is a typical geometric nonlinear problem.

Studies have shown that, for a suspension cable with a small sag and large tension, it is possible to obtain high accuracy when assume the cable as a straight bar approximately with finite element method

(Shen *et al*. 2004). For the pre-tensioned cable of AERORail structure, the tests are needed to prove whether the relationship between tension and load meets the rules. Especially, when the load moving on the cable structure, the structure performances need to be proved with tests.

In short, the AERORail structure has the common characteristics of a general cable as well as its own characteristics.

3.2.2 Simplified analysis model for AERORail structure

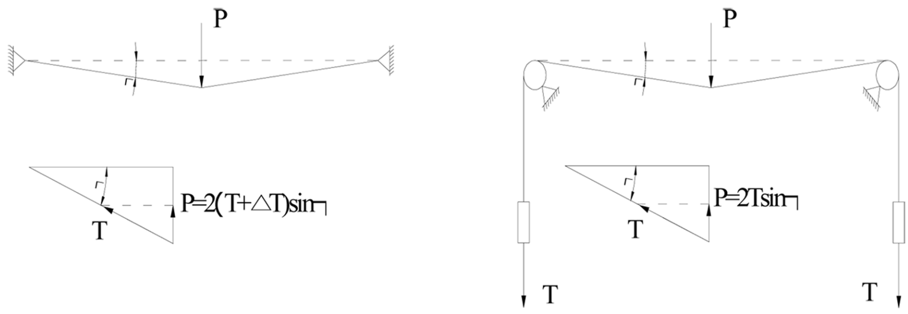
An important feature of AERORail structure is a very small deflection in the service state. The tension force of the cable can be regarded as constant, no matter how the form of support changing (regard the support without vertical displacement). Therefore, for the continuous cable structure, the cables can be regarded as the same mechanical properties structure.

Similarly, according to the cable force in equilibrium under the action of concentrated forces, namely using the balance of force P in Fig. 3, when the vertical deflection of cable is small, the angle β will be small too, and the increment ΔT of cable tension is relative to the cable elongation. It is easy to see that the tension increment ΔT is very small, and therefore, the cable tension can be regarded as constant.

In view to this feature, the structure can be simulated with a rope and pulley model(Unitsky 2004). Shown in Fig. 3, in the rope-pulley system, rope tension does not depend on the external load (P) while is always equal to the tension (T). This "rope-pulley block" simple model is one theoretical basis of the long AERORail cable structure. To some extent, this conclusion may be applied to the design for multi-span continuous structure to reduce the number of anchorage systems for the economy of the AERORail system.

The limitation ratio of deflection to span of simply supported beam is 1/600 (China 2004). Considering this requirement, in the Fig. 6, the allowable loading P should be less than $0.007T$.

Because the AERORail system needs to use high-speed operation to achieve its commercial value, the structure not only needs to meet the deflection under static load, but also needs to meet the maximum dynamic deflection under high-speed vehicle load. Referred to the deflection specification of China's high-speed train bridge(Han 2011), for a 40 m span simply supported bridge, the maximum allowable ratio of deflection to span is 1/1000, the corresponding load P should be less than $0.004T$. Based on this requirement and corresponding service load, this paper designed and completed the corresponding structural model to complete the basic performance test.



(a) End fixed model (b) Pulley block model

T-tension force; P-external load; β-angle

Fig. 3 Balance of the cable under concentrated load

4. Pre-tensioned cable rail model tests

4.1 Test model design

In order to verify the actual effect of cable stiffness, especially for special span and special tension force under special load, the following model tests are designed considering the factors for practical application in the future. The tests will gain more performance issues, which will be helpful for the in-depth research, especially can provide a reference for experimental prototype structure.

Based on a prototype structure with 63 m span, the designed test model can simulate a single-span structure with an actual clear 60 m span, or three-span continuous structure with 20 m span. The 1:15 ratio scale model is showed in Fig. 4. The cables were anchored on the frame columns, which were welded with the base beam. Whole frame has sufficient rigidity. There are two cables, which are high-strength steel wires (diameter = 5 mm, elastic modulus $Es = 1.95 \times 10^5$ MPa, Ultimate Strength f_y = 1980 MPa).

The test contents of the first phase include:

(1) The deflection of a naked single-span cable structures under static load;

(2) The deflection of cable with rail structure under static load;

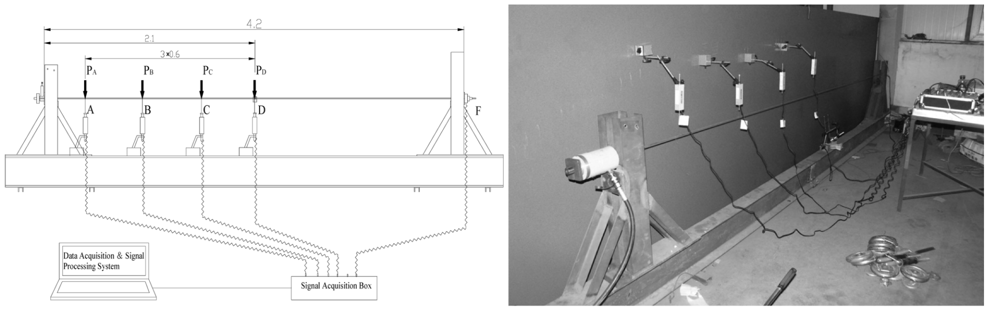
(3) The dynamic change of cable tension with rail structure under moving load.

Based on the foregoing theoretical analysis, the tests are designed for several grade tension forces with different grade static loads located different position. The purpose is to get the elastic stiffness effect, which entirely depends on the stress stiffening of the cable generated by the tension force.

4.2 Single cable tests under static load

As the main support system, the actual stress state of AERORail cable, especially in a different state of deflection under load will directly affect the vehicles safety and structure stability. In order to obtain the cable properties with a certain span under different loads and different tension force, as shown in Fig. 5, a single cable model is tested under different load distribution to get the cable deflection characteristics, the result is a basis for the next double cable structure.

60 groups of tests were completed, including five grades tension force (5 kN, 10 kN, 15 kN, 20 kN and 25 kN). For each grade tension, respectively, three grades load (4.6 kg, 9.2 kg and 13.8 kg) were acting on the different position to test deflection. Respectively, the relationship between tension and load is shown in Fig. 5~Fig. 8. Through zero initialization, all deflections in the diagram are without



(a) Layout of model test (b) Single naked cable test site

Fig. 4 Single naked cable model test

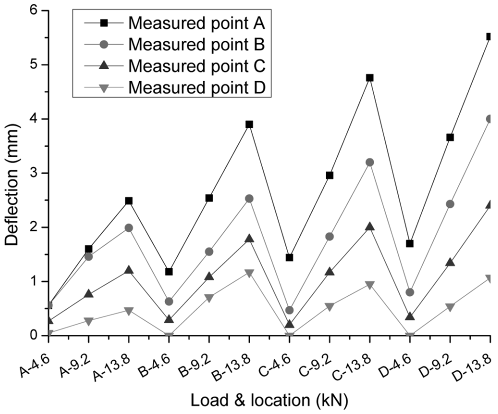


Fig. 5 Cable deflection under 25kN tension force and different loads

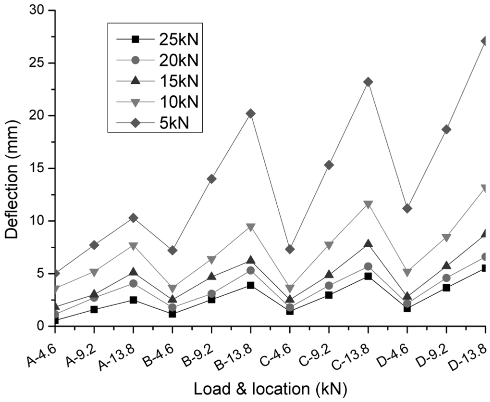


Fig. 6 Deflection of different points under different grade tensions and loads

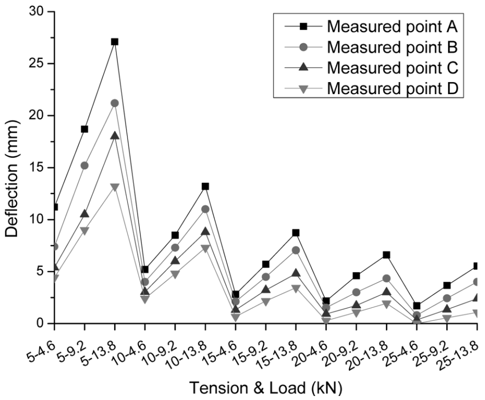


Fig. 7 Deflection of point D under different tension force with three grade loads

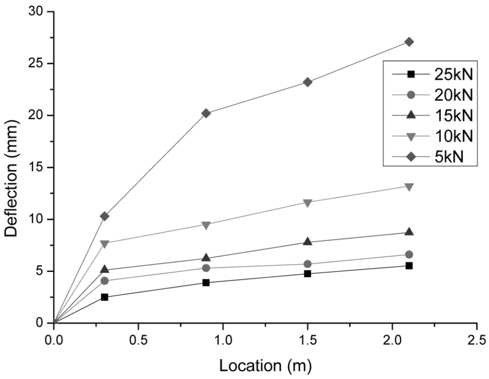


Fig. 8 Deflection when maximum load located at different points

weight action.

The relationship between the deflection of point D under different tension force and different grade loads are shown in Fig. 7.

Under different tension forces with different loads located from point A to Point D, the deflections of cable are shown in Fig. 8.

From the results, we can draw the following conclusions:

(1) It can be seen from Fig. 8, the effect of the cable stiffness by the maximum load at different location, is not as clear as a flexibility string, while like a beam under a concentrated force. However, the large deflection at span middle point under the largest tension force, gradually close to other parts. Especially under the last two grades loads, the effect of concentrated force almost disappeared. That is to say, for a specific span ranges under specific loads, the deflection of whole span is essentially at the same level. This conclusion can be auxiliary to determine the minimum service load.

(2) In order to determine the rule of the actual deflection under the maximum tension and maximum load conditions, here drew the different deflection of whole span under different tension with different

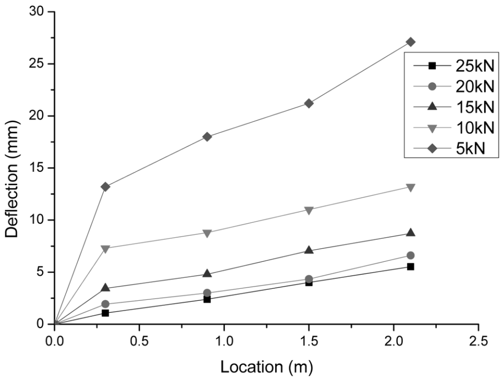


Fig. 9 Deflection of cable when load located at point *D*

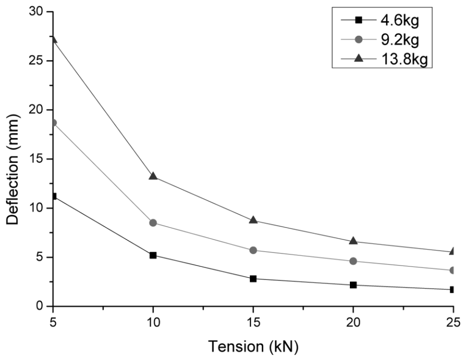


Fig. 10 Deflection of point *D* under different tensions and loads

load grades as shown in Fig. 9. It is shown that when the tensions force is larger in some degree, the effect on the deflection of maximum load at span middle point is smaller. Compared with low-tension conditions, under the maximum tension, the cable line-type deflection is almost no longer increasing.

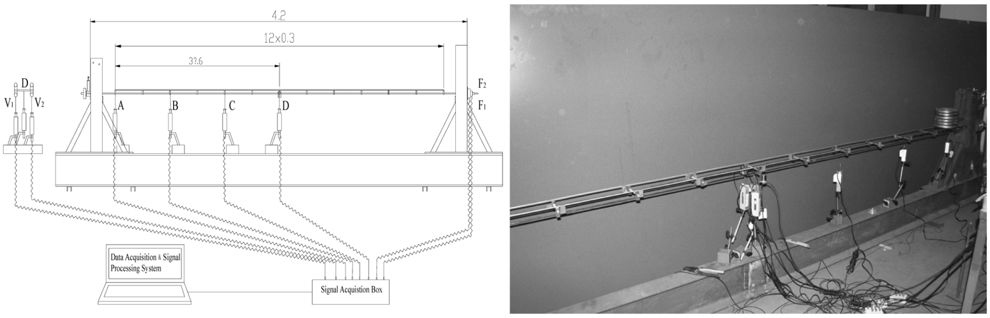
(3) Fig. 10 is the whole-span deflection curves when the load located at point *D* under different load and different tension. It is shown that if the load is smaller than 9.2 kg, the deflection will be linear with tension if the tension force is larger than 15 kN.

Based on the above three results, the necessary conditions for a reasonable structure under specific tensions and specific loads can be integrated to determine. In summary, the first result is to determine the influence under moving loads in a continuous cable, and can help to weaken the bump for the uneven line between supports and span middle. The second result will be helpful to determine the maximum allowable deflection of the structure and set pre-camber. The last result can be used to obtain a particular load under the most economical tension. Of course, the specific control targets must be combined with deflection increment under dynamic load and the allowing cable tension.

4.3 Model tests of double cable integrated rails structure

For the test with double cables, there is a pair of vertical supports on the two cables in transversal direction at intervals of 30 cm, which are linked with a transverse bar. On the vertical supports, there are two cables as the rails without tension force, just fixed with the supports (See Fig. 11). At the anchored end, there are one static sensor and one dynamic sensor. The static sensor will measure the real stretch force; the dynamic one is to measure the dynamic change of tension in real time with a moving load. At the other ends of the cables, there is a mini jack to stretch the cable. According to the mentioned theory about continues cable, at the first phase for study, this paper only report the static tests results of a single span model.

Double cables with rails model of static test are used to test the whole performance of the integrated structure. Tests objective is to determine whether the upper rails with the lower cables structure has the same behaviors of the single naked cable. It should be noted that relative to the naked cable test, here, although the total load has been increased, but because there are double cables to share the load, the load on each cable is reduced.



(a) Layout of model test (b) Integrated rails structure test site

Fig. 11 Single naked cable model test

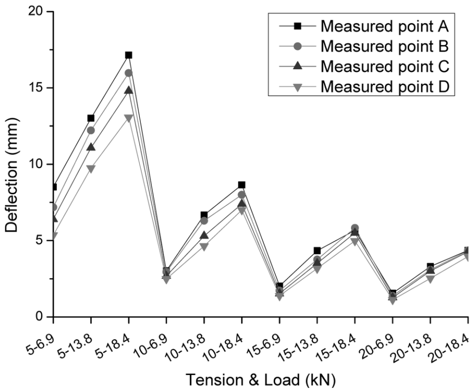


Fig. 12 Deflection of point *D* under different force with three grade loads

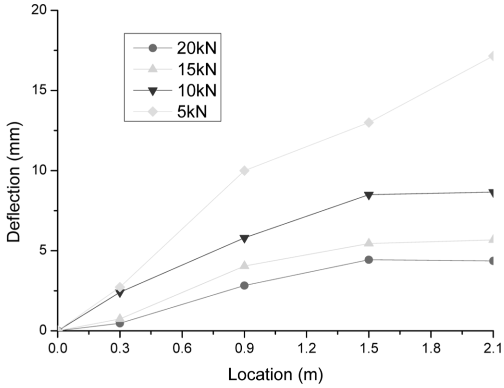


Fig. 13 Deflection when maximum load tension located at different points

There are 48 groups of tests for four tensions (5 kN, 10 kN, 15 kN and 20 kN) and three loads (6.9 kg, 13.8 kg and 18.4 kg) combination. To compare with the naked cable results with the same curves, Fig. 12~Fig. 15 show the same relationship between deflection and tension or load.

When the load was located at middle span point *D*, the deflection was shown in Fig. 14. Compared with Fig. 9, the regularity has more changes.

According to the relationship between the deflection and the load or tension, the assembled structure has the similar regularity with the naked cable. However, the deflection of adjacent points is obviously smaller even under the largest load with a small tension. Especially, the deflection near to the two ends of the cable reduced significantly. Judged from the experiment, under the last grade load (18.4 kg), the change of deflection almost has stabilized when tension is 15 kN. More tension increase will only lead to the increase of construction cost and construction difficulty.

From the results of naked cables and assembled structure, we can draw the following conclusions:

(1) Although the rails are integrated at the last stage, they connect the bottom cables with vertical support bars and the distance between the cables and rails is short. The significant spatial-double cable structure will be invisible, but the upper layer rails still have effect on the structural stiffness to a certain extent.

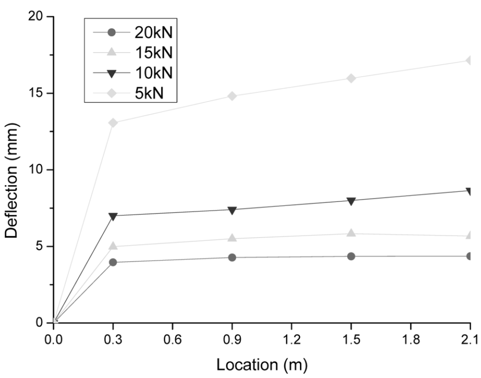


Fig. 14 Deflection of cable when load located at point *D*

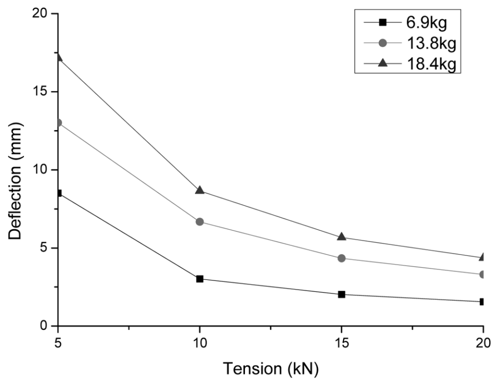


Fig. 15 Deflection of point *D* under different tensions and loads

(2) The concentrated load is located on the upper layer (rails), and will be transferred to the bottom layer (cables) through the vertical bars, but it only can be spread to a small range for the small interval of the vertical bars, even it still reduces the role of a concentrated load.

(3) When the cable tension and the load is small enough, cable deflection regularity is not obvious, because the cable and rail interaction is coupled with the model size effect and the boundary constraint effects. To some extent, it was proved that the minimum cable tension is necessary.

However, in view of the structural stiffness beneficial effect by the upper rails, and only the bottom cables for structure design is feasible in a simplified way. For a real structure, size and boundary effects need to be verified again, and may be necessary to consider the cable and rail structure combined stiffness and in order to obtain the most economical design.

4.4 Comparation of the deflection between theory and test

For a real structure, the weight deflection is easy to offset with pre-camber, so the actual deflection of the AERORail structure caused by the vehicles is major calculation task. According to Eq. (5), even in the smallest tension (5 kN), the λ^2 is almost equal to zero, so the deflection can be obtained because the classical string theory is applicable.

The data in Table 1 are the maximum deflections calculated by the classical string theory under the maximum loads located at the span middle point, and the results measured in the tests.

As shown in Table 1, when the tension is small, the error of combined structure between test and theory is larger than the naked cable. When the tension is increased, the error becomes smaller. In fact, the increase of tension does not directly affect the error. After all, the values of l^2 is almost close to zero at the minimum tension. The basic reason is boundary constraint of the small test model, and rigid body influence by the integrated structure of cables and rails, especially the contribution of the rails to the model structural stiffness. This leads to the inaccurate result by the simplified calculation, which is consistent with the experimental results. However, when the tension is large, the change law of the deflection is closer to the classical string theory with large pretension force.

It can be drawn that when the location of load is far away from span middle point *D*, the corresponding error between theory and test will increase. If the load is located at point *B*, the error almost reaches 20%. It proves the original assumption is not appropriate if the stiffness contribution of

Table 1 Deflection of theory and tests

	Naked cable				Combined structure			
Tension (kN)	Load (kg)	Theory static deflection	Deflection (mm)	Error of test and theory (%)	Load (kg)	Theory static deflection	Deflection (mm)	Error of test and theory (%)
	4.6	9.47	11.20	18.31	6.9	7.10	8.51	19.86
5	9.2	18.93	18.70	-1.23	13.8	14.20	13.02	-8.31
	13.8	28.40	27.10	-4.58	18.4	18.93	17.15	-9.42
	4.6	4.73	5.20	9.86	6.9	3.55	3.02	-14.93
10	9.2	9.47	8.50	-10.21	13.8	7.10	6.67	-6.06
	13.8	14.20	13.2	-7.04	18.4	9.47	8.65	-8.63
	4.6	3.16	2.81	-10.95	6.9	2.37	2.02	-14.65
15	9.2	6.31	5.71	-9.53	13.8	4.73	4.34	-8.31
	13.8	9.47	8.73	-7.78	18.4	6.31	5.67	-10.16
	4.6	2.37	2.17	-8.31	6.9	1.78	1.55	-12.68
20	9.2	4.73	4.6	-2.82	13.8	3.55	3.30	-7.04
	13.8	7.10	6.6	-7.04	18.4	4.73	4.36	-7.85
	4.6	1.89	1.7	-10.21				
25	9.2	3.79	3.66	-3.35				
	13.8	5.68	5.52	-2.82				

the rail can be ignored. The model size effects indicate that large-scale model validation is required.

Taking all above results into account, we can know the static deflection calculated with the classical string theory of the cable is simple and effective when the tension reaches a certain extent, but for cable-rail combined structure, further researches are needed to study the spatial structure influence of the upper rails on the stiffness.

4.5 Tests on dynamic tension increment of cable

Using the double cable with rail structure model (shown in Figs. 12 and 13), the corresponding tension increment under the moving load has been tested. When the vehicles moving along the rail, the tension change will be measured with two dynamic pressure sensors located at the cable end (point F in Fig. 12). Table 2 lists the change under different moving load when the tension is at 2.5 kN, 7.5 kN and 15 kN. It is clear that at the design speed range 1.0~2.0 m/s, the change amplitude of the tension is related to original tension and moving load. When the moving load increases and tension reduces, the change of tension will increase.

Fig. 16 is a typical curve of the tension increment when a load moving along the rail. When the cable tension is 2.5 kN, the increase force is 28 N, only 1.1% to original tension. When the cable tension is increased to 7.5 kN, the maximum variation is only 0.7%. When the cable tension is 15 kN, at the same moving load grade, the tension change is only 0.27%. So when the tension reaches a certain value, the tension changes of the cable can be ignored, then the cable structure analysis can be simplified. At the same time, this small change in the cable is very beneficial for its anti-fatigue ability.

Considering similar loading conditions, the same tension was chosen to analysis the behaviors of the structures. That is, for moving load test, naked cable test and combined structure tests, after compared their results under 15 kN tension with loads, the result is relatively close. (1) For moving load (Second

Table 2 Dynamic increase of tension

Test No.	Tension (kN)	Vehicle load (kg)	Maximum increase of tension (N)	Average increase ratio
1	2.5	3.8	19	0.8%
2	2.5	8.0	28	1.1%
3	7.5	3.8	16	0.2%
4	7.5	8.0	25	0.3
5	7.5	14.3	56	0.7%
6	15.0	3.8	26	0.15%
8	15.0	8.0	26	0.17%
9	15.0	14.3	41	0.27%

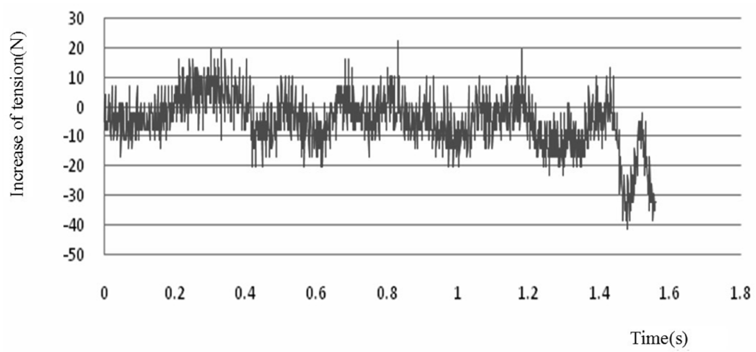


Fig. 16 Time-histories curve of string force with moving load

grade load 14.3 kg), the stress increment is 41 N. (2) For naked cable (Third grade load 13.8 kN), the static deflection of middle span is 8.73 mm, with a simplified method in Fig. 3, calculated the stress increment 33.1 N, while with the theoretical method, the increment is 38.9 N, close to the measured results. (3) Corresponding to the integrated structure test, there is no same load grade, here we used the approximate load to compare the results. We know the previous analysis results is based on the elastic stiffness, although it does not fully meet the non-linear relationship, it still can be approximated with the average of the first grade load (6.9 kg) result and the third-grade load (18.4 kg) result. The equivalent load is only 12.65 kN for one single cable. Under this equivalent load, the average measured deflection is 5.84 mm. Using the simplified method in Fig. 3 can calculate the incremental force 14.8 N, smaller than the theoretical value 18.4 N.

Under dynamic load, all the tension increments are greater than the test and theoretical values. The naked cable results are closer to the theoretical values. However, the results of cable and rail combined structure are smaller. The reason should be subject to the coupling effect of combined structure and the moving loads. However, less than 1% of the cable force increment is not obvious, and can be ignored.

According to the above theoretical analysis and experimental results, for the AERORail structure, when the rise-span ratio is relatively small, it can be assumed that the tension of entire span is the same under the static load; under the dynamic load, it can be assumed that change of tension is small and can be reasonably ignored too. For the future practical engineering, this conclusion will be an important foundation for the allowable load selection for this structure.

5. Conclusions

(1) For a particular span of the suspension cable, when the cable tension is below a certain value, the gravity stiffness performance is significant, but when the cable tension is increased to a certain value, the elastic stiffness will be dominant. From the initial loose state to the end tense state, cable axial stiffness changes dramatically, the relation between the tension and the deflection is obvious nonlinear in the early stage, while this nonlinear characteristic is inconspicuous in the end stage. In fact, when the cable tension reaches a certain value, the extension of the cable is controlled by the tension. According to the material properties of the high-strength cables, the elongation is very limited. This is a theoretical basis for AERORail structure using high-strength metal cable.

(2) According to the change principle of stiffness, in the design, in order to quickly gain the accurate mechanical properties of the AERORail structure, when the minimum deflection-span ratio was determinate, the reasonable deflection is easy to achieve under the dynamic load and static load. Referring to the allowable deflection of the bridge of high-speed trains of China, the concentration service load is only 0.4% of tension force.

(3) When the rise-span ratio is smaller, it can be claimed that the cable's tension of continuous span is the same under the static load. Test results proved that even the deflection would be increased under the vehicle-moving load, but the deflection is still smaller and cannot affect the tensile stress of cable observably. Therefore, the tension regarded as a constant is reasonable. This conclusion will be helpful to determine the allowable load for AERORail structure. For this structure, due to the relatively small rise-span ratio, even under moving load, the cable tension changes less than 1%, which is favorable to the cable's anti-fatigue ability

(4) Because the rise-span ratio of AERORail structure must be controlled in a small range (less than 1/1000), the contribution of the gravity stiffness to the axial stiffness is even smaller, and can be ignored, then the axial stiffness can be replaced with the elastic stiffness. This is the reason why more accurate result can be gained with a simplified calculation method.

(5) According to test results, the relationship between deflection and tension and load can be determined, and that is helpful to the design with an economic section of cables.

Acknowledgements

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