Analysis of Static and Dynamic Behavior of T-shape Beam Reinforced by External Prestressing Tendon

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Abstract

External prestressing has become a primary method for strengthening existing concrete beam and has been increasingly used in the construction of newly erected ones, particularly railroad bridges in recent years. In order to evaluate the effect of this method, the static and dynamic behavior of a T-frame beam reinforced by external prestressed strengthened concrete beam was analyzed by 3D finite element method, and the field test study was also made. The study was carried out to further investigate the simply supported reinforced prestressed concrete beam strengthened by external prestressing through theory analysis and experiment.

Keywords: *External Prestressing, Reinforcement, Numerical Simulation, Displacement, Concrete Compressive Stress.*

1. Introduction

With the development of transportation facilities, in order to adapt the need of market economic development, the railway excavates existing line potential and enhances transport capacity through operating heavy haul trains and improving train speed while accelerating to build new lines at the same time. Especially after the implementation of tow transport and container traffic, the safety capacity of many old bridges are insufficient because the bridges on existing lines are designed and built according to the old design specification. There are many problems universally existing such as the bridge of displacement caused by the vibration of vertical and transverse are more larger, crack resistance and dynamic coefficient of some key parts do not meet the operation security and so on; and these problems are relevant to too many times of revising specification[1]. Railway bridge design specification has been carried on many times of revision combined with the actual problem, which causes technical standards used for design of concrete beam on existing lines to have certain differences. Therefore, although design loads of most bridges adopt China railway standard -22 level and part of them are China railway standard -26 level, part of them also adopt downgrading and load standard is China railway standard -21 level, and even lower of China railway standard -20 level. Especially early specifications have inadequate understanding for prestressed long-term loss of prestressed concrete beam (shrinkage and creep of concrete and relaxation of prestressed steel), thus vertical displacement, vertical frequency and crack resistance of existing beam can't meet the requirements according to current standard to test[2-4]. Therefore, reinforcing the old bridges to satisfy current requirement of 200 km/h is one of the main tasks of bridge construction.

The national railway goes through large-scale acceleration for six times. For the early design of prestressed concrete simply supported T beam, the problems of vertical impact load significantly increasing, obvious beam vertical vibration, deficient concrete crack resistance, Train ride comfort greatly reducing will come out when the speed of trains is 200km/h and that of freight trains is 80km/h. Vertical impact load of the trains increases, and especially the influence to locomotive with prefix Z is most significant. Because high-speed locomotives of new type like DF11G are hanging two-shipper, axle load is 230kN, unsprung mass is bigger, and impact load after acceleration has also increased. When the Z-prefix speed-increasing train passes the bridge, vertical displacement of the bridge is significantly increased. At the same time, significant vertical vibration occurs on the bridge [4][5].

2. vehicle-bridge dynamical analysis

The constant force moves to the right with a constant velocity on the simple supported beam as shown in Figure1[6-9], the mobile vehicle inertial characteristic was ignored and mobile vehicle was regarded as a constant force. The variable coefficient vibration equation was avoided by this way. From zero time to time t, fore moves from left end supporting to right at υ(see Fig.1). From vibration analysis the vibration differential equation of the beam was represented by the formula (1):

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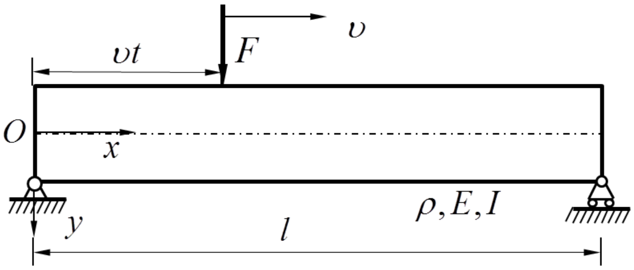

Fig.1. The constant force through the simple supported bridge with constant speed

$$EI\frac{\partial^4 y}{\partial x^4}+\rho A\frac{\partial^2 y}{\partial t^2}=p(x,t) \tag{1}$$

in which E=modulus of elasticity of beam; I= moment of inertia for transformed cross section taken about the centroid; A= transformed area of beam cross section and ρ= material density. Assume that the dynamic displacement of the forced vibrations $y(x,t)$ can be expressed as series form of vibration mode:

$$y(x,t)=\sum\varphi_n(x)q_n(x) \tag{2}$$

in which $\varphi_n(x)$ = simply supported beam displacement = $\sin(\frac{n\pi x}{l})$. The forced vibration equation can be gotten by putting the formula (2) into the formula (1) and the orthogonality of vibration mode.

$$EI\sum q_n(t)\frac{d^4\varphi_n(x)}{dx^4} + \rho A\sum\ddot{q}_n(t)\frac{d^2q_n(x)}{dt^2}=p(x,t) \tag{3}$$

Using the standardization of vibration mode, the formula (3) times $\varphi_k(x)$, then integral in the range 0 to l, the left of item exist only when $k = n$, others was zero. Leading to form:

$$EIq_n(t)\int_0^l\varphi_n(x)\frac{d^4\varphi_n(x)}{dx^4}dx +\rho A\frac{d^2q_n(t)}{dt^2}\int_0^l\varphi_n^2(x)dx =\int_0^l\varphi_n(x)p(x,t)dx \tag{4}$$

Simplified formula (4), leading to forced vibration differential equation:

$$\ddot{q}_n(t)+\omega_n^2q_n(t)=Q_n(t)\quad(n=1,2\cdots N) \tag{5}$$

In which

$$\omega_n^2=\frac{EI\int_0^l\left[\frac{d^2\varphi_n(x)}{dx^2}\right]^2dx}{\rho A\int_0^l\varphi_n^2(x)dx},$$

$$Q_n(t)=\frac{\int_0^l p(x,t)\varphi_n(x)dx}{\rho A\int_0^l\varphi_n^2(x)dx}$$

So constant moving single constant force, generalized excitation force

$$Q_n(t)=\frac{\int_0^l F\delta(x-\upsilon t)\varphi_n(x)dx}{m\int_0^l\varphi_n^2(x)dx} =\frac{2F}{\rho Al}\sin(\Delta_n t)\quad(n=1,2\cdots N) \tag{6}$$

in which $\delta(\xi)$ Draco function, it is defined as:

$$\delta(\xi)=\begin{cases}1 & \xi=0\\ 0 & \xi\neq 0\end{cases} \tag{7}$$

The forced vibration equation can be gotten by putting the formula (6) into the formula (5).

$$\ddot{q}_n(t)+\omega_n^2q_n(t) =\frac{2F}{\rho Al}\sin(\Delta_n t)\quad(n=1,2\cdots N) \tag{8}$$

When the time is 0, the system is in a static state, the formula (8) can be obtained.

$$q_n(t)=\frac{2F}{\rho Al}\frac{1}{\omega_n^2-\Delta_n^2}(\sin\Delta_n t-\frac{\Delta_n}{\omega_n}\sin\omega_n t) \tag{9}$$

In which $\omega_n^2=\left(\frac{n\pi}{l}\right)^2\sqrt{\frac{EI}{\rho A}}$ = the natural frequency of simply supported beam and $\Delta_n=\frac{n\pi\upsilon}{l}$ = the generalized excitation frequency of moving load.

Therefore, the dynamic stress of the beam is expressed as:

$$y(x,t)=\frac{2F}{\rho Al}\sin(\frac{n\pi x}{l}) \sum\frac{1}{\omega_n^2-\Delta_n^2}(\sin\Delta_n t-\frac{\Delta_n}{\omega_n}\sin\omega_n t) \tag{10}$$

Where formula (10) the first item in the brackets represent a forced vibration the second one expressed the free vibration.

3. Establishment of finite element model

This paper adopts large and universal finite element software Ansys to conduct analog computation[10][11], solid 45 element to model for T beam and constraint processing form which is basically in agreement with the reality, that is, the panel point of horseshoe part ux = uy = uz =0, the other part of horseshoe uy = uz =0; the prestressed bars uses link8 to imitate, the impacts of other stirrup on beam shall take the way of improving concrete elastic modulus (E) to achieve. The reinforcement materials mainly used are as follows: adhesive plate, external cable (including calculating steering position of external cable and the position of anchoring in the upper). Calculate compressive stress and vertical displacement of structural concrete of T beam before and after reinforcing above materials. Finite element model include that bridge and gravel and rails like shown in Fig.2. Fig.4 and Fig.5 show the typical constitutive law of materials for steel reinforcement and prestressing steel, concrete[12-15].

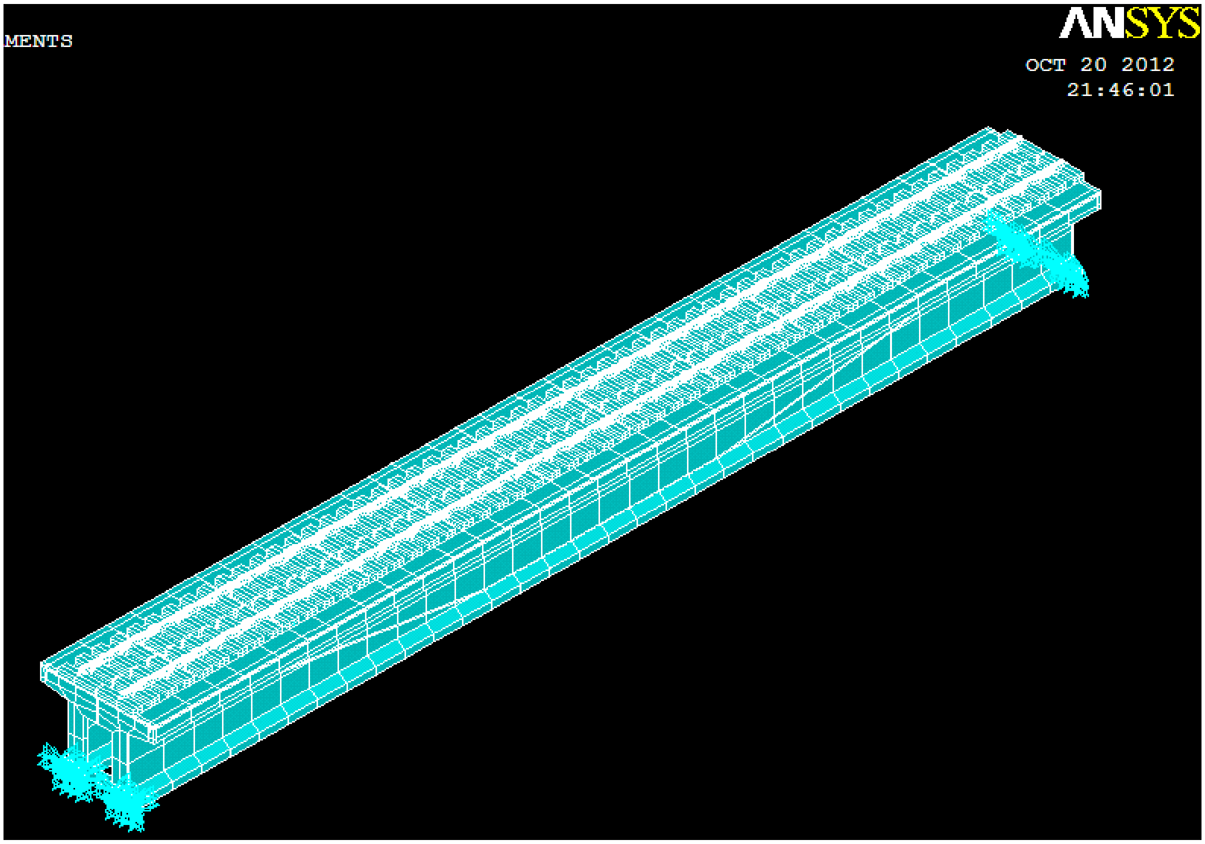

Fig.2. finite element model

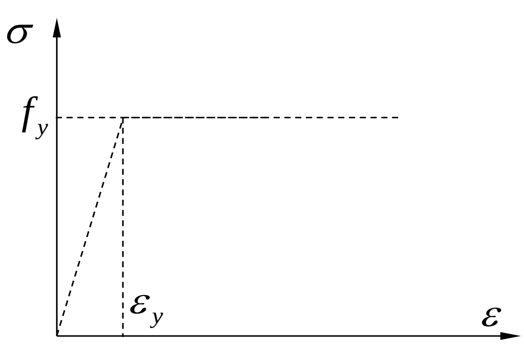

Fig.3. Constitutive law for steel reinforcement

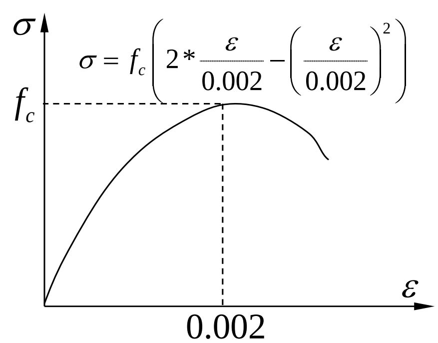

Fig.4. Constitutive law for concrete

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4. External prestressed strengthened concrete beam calculation

4.1 Advantages and disadvantages of common reinforcement methods

Common reinforcement methods in engineering: reinforcement of continuous beam, thicken and widen of upper and lower flange, adhesive plate of lower flange, adhesive fiber of lower flange, external prestressed steel wires. The two forms of continuous reinforcement and thicken and widen of upper and lower flange need to interrupt traffic. This goes against with maintaining the existing traffic order and shall not be used in practice. Adhesive fiber and plate reinforcement adept to the existing reinforced concrete bridge structure. Corrosion of reinforcement and other reasons cause the weakening of primary structural bearing capacity. They are the methods to recover primary structural design or increase the structural bearing capacity. This method has some defects, the improvement of primary structural bearing capacity is not obvious and it cannot play a part obviously in improving the concrete crack resistance. Thus, the two reinforcement methods are seldom adopted or only used in the reinforcement of reinforced concrete structure. The effect of external prestress wire on beam reinforcement is most obvious, its characteristics after reinforcement are:

(1) Structure weight remains unchanged and the bearing capacity can be increased dramatically;

(2) The prestressing steel reinforcement allows negative vertical displacement of the bridge structure and inverted arch to some extent occurs on the beam;

(3) The construction is convenient and quick and economic benefits are significant;

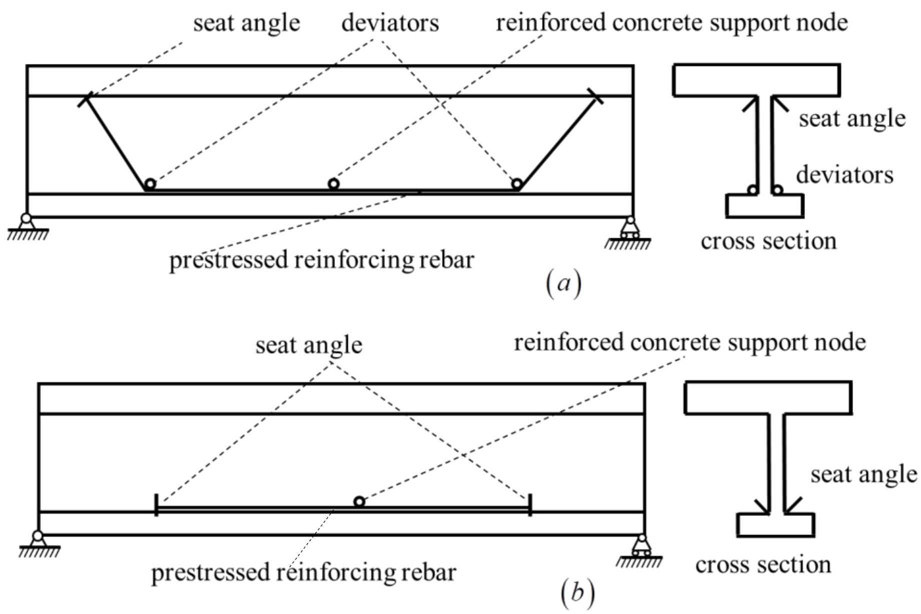
(4) The construction process has little impact on the traffic;

(5) The construction does not damage original structure and almost does not change the bridge substructure space;

(6) Prestress can be adjusted according to the need, and prestressed tendon changes.

4.2 External prestressed reinforcement beam calculation

In the external prestressed reinforcement of simply supported girder, the main four layout forms are shown in Fig.5.



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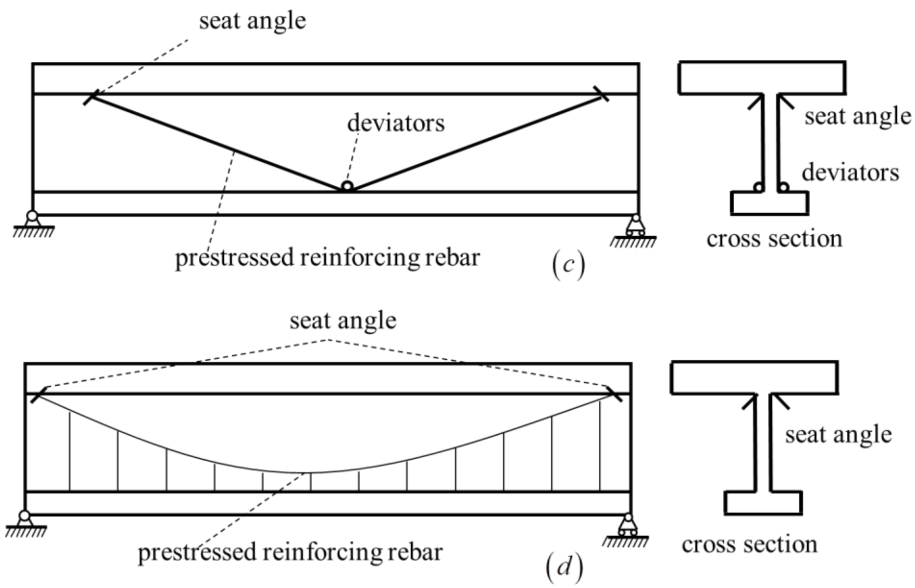

Fig.5. Arrangement of external reinforcement

If the four reinforcement layout forms shown in Fig.5 are adopted and prestressed tensile stress is taken as the strength limit of 0.6*f*, 0.65*f*, 0.7*f*, 0.75*f* and 0.8*f*, the calculation results of vertical displacement of the mid-span and the compression stress of the concrete on the lower side are shown in table 1and table 2.

Table 1. The mid-span vertical displacement of the four reinforcement layout forms

Ultimate multiple	0.6	0.65	0.7	0.75	0.8
Distance of 3.2m(in:mm)	22.03	21.15	20.12	19.94	19.65
Distance of 4.8m(in:mm)	22.63	22.01	21.23	20.32	19.98
Distance of 8.0m(in:mm)	23.33	22.63	21.93	21.08	20.11
Distance of 12m(in:mm)	22.24	21.90	21.05	20.02	20.06

Table 2. The lower side concrete's compression stress of the four reinforcement layout forms

Ultimate multiple	0.6	0.65	0.7	0.75	0.8
Distance of 3.2m(in:MPa)	5.353	5.558	5.761	5.965	6.17
Distance of4.8m(in:MPa)	5.380	5.587	5.793	6.000	6.206
Distance of 8.0m(in:MPa)	5.008	5.200	5.386	5.574	5.763
Distance of 12m(in:MPa)	5.138	5.338	5.537	5.737	5.936

For the reinforcement layout form shown in Fig.5 (a), if the distance between deviators is: 3.2 m, 4.8 m, 8 m and 12 m and prestressed force is 0.6*f*, 0.65*f*, 0.7*f*, 0.75*f* and 0.8*f*, the calculation results of the mid-span displacement and the compression stress of the concrete on the lower side are shown in table 3 and table 4.

Table3. The mid-span vertical displacement of the four reinforcement layout forms

Ultimate multiple(*f*)	0.6	0.65	0.7	0.75	0.8
Figure 2. (a) reinforcement mode(in:mm)	21.02	20.75	20.01	19.72	19.45
Figure 2. (b) reinforcement mode(in:mm)	20.87	20.68	19.93	19.69	19.43
Figure 2. (c) reinforcement mode(in:mm)	20.73	20.56	19.82	19.61	19.35
Figure 2. (d) reinforcement mode(in:mm)	21.95	21.23	20.22	19.90	19.67

Table 4. The lower side concrete's compression stress of the four reinforcement layout forms

Ultimate multiple(*f*)	0.6	0.65	0.7	0.75	0.8
Figure 2. (a) Reinforcement mode(in:MPa)	5.385	5.590	5.795	6.005	6.210
Figure 2. (b) Reinforcement mode(in:MPa)	5.425	5.635	5.844	6.054	6.264
Figure 2. (c) Reinforcement mode(in:MPa)	5.444	5.655	5.866	6.077	6.287
Figure 2. (d) Reinforcement mode(MPa)	5.208	5.405	5.686	5.904	6.105

The analysis of prestressed force value, deviator position and end anchorage position is provided as follows:
As shown in table 1 and table 2, the compressive stress of concrete in four kinds of external prestress arrangement modes in fig.5 are linearly increased; a and b increases more quickly, but b is anchored on the end of the beam; so it shall not be taken in to consideration as construction for strengthening will influence the traffic.

As shown in table 3 and table 4, the compressive stress of concrete in four kinds of external prestress arrangement modes in fig.5 are linearly increased; that is when not taking the steering angle into consideration, the influence of position of deviators is not big. But in order to prevent heavier stress concentration in beam body, the position of deviators shall be set on the diaphragm plate or on the diaphragm plate directly. In this way, stress concentration of the beam body can be reduced.

For the reinforcement layout form shown in Fig.5 (a), if the distance between deviators is 12 m and relative height of anchorage position ranges from 580 mm to 1,780 mm, the calculation results of the compression stress of the concrete on the lower side are shown in Fig.6.

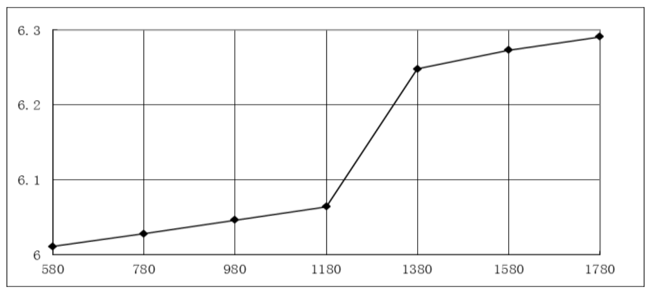

Fig.6 . Horizontal section bar length to 12 m and in different height anchorage reinforcement mode side concrete compressive stress

Fig.6 shows that when the ends are anchored at different relative height, the compressive stress of concrete on the downside of beam body is 6.011MPa at least and 6.291MPa at most with 4.6 % increased which means the position of according point is selectable in actual strengthening according to the convenience of construction.

4.2 Calculation results and experimental analysis comparison

The mode of fig.5(a) is selected and used as actual reinforcing mode, relevant parameters are that intermediate length is 12m and prestress is 1445MPa.The anchor point position of reinforcement shall be determined according to actual position and meet the construction requirements [16][17]. The field experimentation conditions are vibrational state under the function of operating loads after bridge beam is reinforced on JiaoJi line. The vertical maximum amplitude of actual measured beam is 1.01mm and 0.96mm respectively when the speed of the truck is 77 km/h and 74. 9 km/h. They are 1.9mm and 2.1mm which is far less than the requirements of 26.4mm in “Temporary Provisions of Mixed Passenger and Freight Railway of New 200 Kilometers per Hour” after considering dynamic coefficient of live load. It is consistent with the calculation of this paper basically.

5. Conclusions

The research of longitudinal reinforcement of simply supported girder is to ensure that vehicle passes through the bridge safely and that passengers are comfortable. The calculated and experimental results show that external prestressed reinforcement applied on the beam allows fully utilized concrete compression stress and qualified indicators of the bridge.

6. Acknowledgments

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