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Theoretical and experimental study on flexural behavior of prestressed steel plate girders

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ABSTRACT

Applying prestressing techniques increases the load carrying capacity of girders, leading to substantial saving in construction material. In addition, prestressing a steel girder reduces its deflection under external loads, and thus, enhances its flexural behavior. The aim of this study is to use a finite-element formulation to verify the effectiveness of the prestressing technique with respect to the flexural behavior of a steel plate girder. The strength of two steel box girders is tested, one with prestressing (prestressed girder) and one without (control girder). Based on experimental results, a theoretical model is proposed for predicting the flexural resistance of a steel box girder with external tendons. To improve the calculation accuracy, finite-element formulation is applied to prestressing and external loading stages of the girder and external tendons, which are regarded as composite structures, and the interactions between them are fully considered. The friction between tendons and deviators is considerably small. Therefore, the friction resistance between the tendons can be neglected during the force analysis. The strain in the prestressed girder is distributed linearly along its height, indicating that the calculation performed using the plane section assumption is consistent with the actual situation for the same external load. The experimental and theoretically calculated values of strain in the bottom plate of a steel girder and tension force increment for deflections at mid-span and quarter span are in good agreement. This indicates that the finite-element formulation proposed in this study is correct and efficient.

1. Introduction

In recent years, the assessment, maintenance, and strengthening of bridge structures has received considerable attention. External prestressed tendons have been considered as a possible means of strengthening single-span steel–concrete composite beams [1,2]. A prestressed steel girder is typically fixed to high-strength tendons to generate joint forces in a tendon–girder composite bridge. External prestressing, which involves pre-tensioning or post-tensioning, is commonly used for strengthening new or existing bridges because of its effectiveness and economic feasibility [2,3]. Prestressing technology for steel structures may improve their economic efficiency. Efficient steel tendons reduce the size of structural steel members and amount of steel required, while increasing load-carrying capacity. While tendons increase the load-carrying capacity of girders by two orders of magnitude, the actual increase in load-carrying capacity is 70%–80% when buckling is considered [4,5].

In steel structures, prestressing technology can be used to save construction material and improve the stiffness and stress state of the structure [6]. In conventional prestressed steel girder analysis, tension increment in a prestressing cable under external load is regarded as a redundant force, which is solved using the force method [7]. In this analysis, the interaction between a steel girder and cable is considered, and the prestressed steel girder is regarded as a cable-beam structure. The influence of tension force increment is neglected while analyzing the cable and girder using the theory of a suspension girder, and the tension in the cable is considered constant. The basic finite-element equation is simplified to a linear differential equation to calculate the deflection and deformation of the steel box girder [8]. In this study, the analysis of a prestressed simply supported steel box-girder is carried out with full consideration of the interaction between the girder, cables, and tension force increment.

2. Material and methods

2.1. Establishment of basic equations

2.1.1. Analysis of prestressed steel box girder model

A prestressed steel girder is set using high-strength cables in a control steel girder to form a composite girder. Multiple reinforcing rib stiffeners are arranged on the girder span. Steel cables are passed through deviator points on the rib stiffeners and anchored at two ends of the girder. The basic structure of the steel girder and profile tendons is shown in Fig. 1.

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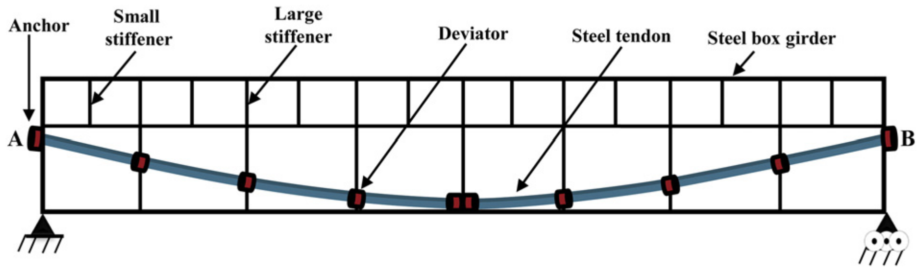

Fig. 1. Construction of prestressed steel box girder with external tendons.

The prestressed steel girder is analyzed in terms of its mechanical characteristics. The girder and tendons are considered as composite structures and analyzed separately. Tendons are analyzed based on theoretical analysis of flexible steel structure members [9]. They are considered as independent members that act on the steel girder through deviator and anchor points. At these points, relative sliding can occur between tendons and girders. We assume there are m deviators in the prestressed steel girder fixed to the rib stiffeners, and $m+2$ contact points (including two end points) between the steel girder and tendons on both sides of the girder, that is, $m+1$ tendon units. The steel girder is divided into n elements, $n = a*(m+1)$ (a is a positive integer), and each deviator corresponds to a node of a girder element. The analytical model of the prestressed steel girder is shown in Fig. 2, in which e_k is the distance of the k^{th} deviator from the neutral axis of the girder.

2.1.2. Finite element formulation of tension force increments in steel tendon

Under external load, relative sliding occurs between tendons and the girder at deviator points. Therefore, in finite-element analysis, the generalized nodal displacement of the girder cannot be used, and tension increment in the tendons can be solved using a strain matrix.

The tension increment in the tendons is related to the deformation of the girder. The elongation of the steel tendon between the two anchored points is equal to the fiber elongation of the steel girder along the projection direction of the tendon. As the friction between the tendon and deviators is considerably small, it can be neglected. The tension force, T, in the tendon is considered constant along the entire tendon [10]. The first set coordinates of the k^{th} deviator under prestressed load ($T = T_0$) are (x_k^0, z_k^0). Under external load and deformation of the girder, the coordinates become (x_k^p, z_k^p), where superscripts 0 and p denote the prestressed and external loads, respectively. The k^{th} deviator corresponds to girder element node i, for the prestressed and external loads. The relationship between the coordinates of the k^{th} deviator can be expressed as follows:

$$\left\{ \begin{array}{c} x_k^p = x_k^0 + u_i - e_k\theta_i \\ z_k^p = z_k^0 + w_i \end{array} \right\} \tag{1}$$

where u_i, w_i, are the displacement components along the x, z axis directions, respectively, and θ_i is rotation component along y axis direction, of node i of the girder element corresponding to the k^{th} deviator under external load, as shown in Fig. 3.

Under prestressed load, the length of the tendon between any two deviators points $(k, k+1)$ is

$$l_{k,k+1}^0 = \sqrt{\left(x_{k+1}^0 - x_k^0\right)^2 + \left(z_{k+1}^0 - z_k^0\right)^2} \tag{2}$$

Under external load, the length of the tendon between any two deviator points $(k, k+1)$ becomes:

$$l_{k,k+1}^p = \sqrt{\left(x_{k+1}^p - x_k^p\right)^2 + \left(z_{k+1}^p - z_k^p\right)^2} \tag{3}$$

Thus, the strain increment in the tendon under external load can be obtained as follows:

$$\Delta\varepsilon^p = \frac{\sum_{k=0}^m l_{k,k+1}^p - \sum_{k=0}^m l_{k,k+1}^0}{\sum_{k=0}^m l_{k,k+1}^0} \tag{4}$$

Considering that the tendons obey Hooke's law, under external load, the tension force increment in the steel tendon, dT, is

$$dT = E_S A_S \Delta\varepsilon^p \tag{5}$$

where E_S and A_S denote the elastic modulus of the tendon and cross-sectional area, respectively.

Therefore, under external load, the total tension force in the steel tendon is

$$T = T_0 + dT \tag{6}$$

2.1.3. Effect of tension force of tendons on girder

The prestressed steel girder is longitudinal; therefore, the plane section assumption is used in the analysis of the girder in this study. Under external load, the girder is displaced and the shape and force of

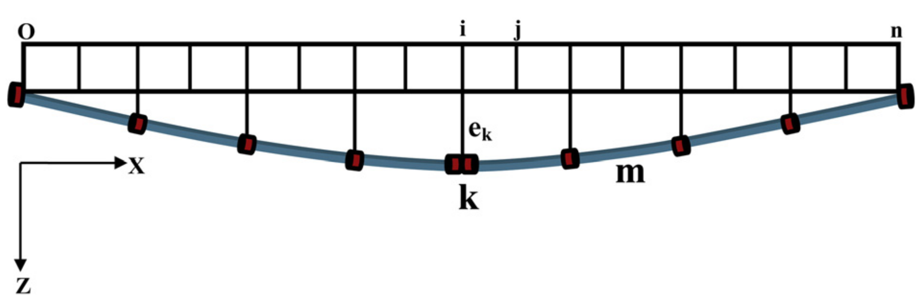

Fig. 2. Analytical model of prestressed girder, where e_k = the distance of the k^{th} deviator from the neutral axis of the girder, k = the deviator, m = the number of deviators, (n, o) = the tow end point of girder, i = point in mid span of girder.