Engineering Structures 42 (2012) 1–8

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Behavior of precast prestressed concrete bridge girders involving thermal effects and initial imperfections during construction

Jong-Han Lee *

School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 10 December 2010
Revised 20 January 2012
Accepted 8 April 2012
Available online 18 May 2012

Keywords:
Precast prestressed concrete
AASHTO-PCI standard girder
Thermal effects
Elastomeric bearing
Nonlinear finite element

ABSTRACT

The instability of precast prestressed concrete bridge girders during construction have been of particular concern to bridge engineers. After they are installed on bearing supports, prestressed concrete girders are immediately subjected to environmental thermal loads that may be exacerbated by fabrication and construction errors. Thus, in this research, the environmental thermal loads, which cause extremes in thermal deformations in precast prestressed concrete girders, were determined. Then a three-dimensional nonlinear finite element sequential analysis procedure was developed to evaluate the behavior of a precast prestressed concrete girder subjected to both thermal loads and geometry and support imperfections during each construction stage. This analysis indicated instability in a 30-m long prestressed concrete BT-1600 girder when total lateral deformation in the middle height of the girder at mid-span exceeded about 25 cm.

1. Introduction

Since the advent of precast prestressed concrete girders in bridge design and construction, the demand for a more expansive girder span, which would reduce construction costs and improve bridge esthetics, has been increasing. However, the lengthening of girders with deeper precast sections and high-strength concrete increases the likelihood that the girders will destabilize. Such failure, one of which is illustrated in Fig. 1, have led to considerable apprehension about the behavior of precast prestressed concrete girders during construction, specifically before the addition of the slab and bracing. One investigation into the collapse of the girders, Oesterle et al. [1] indicated that a combination of several factors, including the initial sweep (or lateral deformation), the thermal sweep, and the support slope, could cause lateral instability of the girders during construction.

The initial sweep of the girder occurs during fabrication, shipping, and handling. During fabrication, the eccentricity of prestressing strands can create an error that leads to unexpected initial sweep in the girder. Then shipping and handling can subject the girder to unaccounted loads or boundary conditions that also affect the initial sweep. When placed on supports that are not level, the girder can also experience sweep. In addition, while prestressed concrete girders are resting on a bearing support, thermal environmental effects can produce additional sweep that may contribute to the instability of the girders prior to the placement of a bridge deck and diaphragms. For the initial sweep in the girder, the *PCI Bridge Design Manual* [2] provides a tolerance of 3 mm per 3 m (1/8 in per 10 ft) of member length. Nevertheless, in practice, this small tolerance value has not been adhered to because of the many unexpected conditions that occur during fabrication and handling, as mentioned previously. However, no study that evaluates the lateral deformation of the girders has been carried out, especially during construction when the girders are subjected to the combined effects of thermal response, initial sweep, and support slope.

Some relevant initial research was conducted by Mast [3,4], who calculated the stability of a girder suspended from lifting devices and transported on elastic supports. Mast proposed a method based on the ratio of a resisting moment at the support to an overturning moment induced by the girder sweep and support slope. The method was adopted in the *PCI Bridge Design Manual* [2] for the evaluation of how safe a girder is from rollover (or overturning) during shipping and lifting. However, the manual provided no specific method or guideline that analyzes the lateral stability of the girders placed on elastic bearing supports during construction. The *AASHTO LRFD Bridge Design Specifications* [5] and the *AASHTO LRFD Bridge Construction Specifications* [6] simply addressed the importance of considering the safety of precast members during all construction stages, but they did not provide any specific guidelines related to the stability of precast prestressed concrete girders during construction.

Thus, as an initial study, this research evaluated the behavior of a precast prestressed concrete girder subjected to the combined effects of the initial sweep, the thermal response, and the support slope during construction. For the largest vertical and lateral

* Tel.: +1 404 894 2278; fax: +1 404 894 2201.
E-mail address: jonghan.lee@gatech.edu

0141-0296/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2012.04.003

Fig. 1. Stability failure of precast prestressed AASHTO Type-V girders during the construction of the Red Mountain Freeway in Arizona [1].

thermal response, the thermal effects of seasonal variations and bridge orientations on vertical and lateral thermal gradients were evaluated for four AASHTO-PCI standard girder sections in Atlanta, Georgia. For a 30-m long prestressed BT-1600 girder, which showed the largest vertical and lateral thermal gradients in the summer and the winter, respectively, the behavior of the girder subjected to the thermal response, the initial sweep, and the support slope was evaluated using three-dimensional (3D) nonlinear finite element sequential analysis.

2. Determination of thermal loads

The primary environmental parameters causing temperature variations in bridges are solar radiation, air temperature, and wind speed. These environmental values were determined from 30-year (from 1961 to 1990) monthly averaged daily solar radiation and climatic data provided by the National Renewable Energy Laboratory [7] for Atlanta. To account for seasonal variations in environmental conditions, this study chose the daily solar radiation values of 21.9, 29.4, 22.4, and 11.9 MJ/m^2 for March, June, September, and December, respectively. The months of March, June, September, and December were defined as representative months of the spring, summer, fall, and winter. The daily maximum and minimum air temperatures for each season were determined from the record maximum temperature and the average daily minimum temperature of the 30-year climatic values, respectively, for the representative months. The average daily minimum temperature was used rather than the record daily minimum temperature since it is highly unlikely that the record maximum and minimum temperatures occurred on the same day. However, since wind speed was minimal on the days when the largest vertical and lateral thermal gradients occurred, this study neglected the effect of wind speed on girder temperatures.

The temporal variation in the daily solar radiation was calculated using the Liu and Jordan equation [8]:

$$I(t) = H\frac{\pi}{24}(a + b \cdot \cos w) \cdot \left(\frac{\cos w - \cos w_s}{\sin w_s - w_s \cos w_s}\right) \tag{1}$$

in which $I(t)$ is the solar radiation at time t on a horizontal surface, H the total daily solar radiation, w the solar hour angle, and w_s the sunrise hour angle; $a = 0.409 + 0.5016 \cdot \sin(w_s - 1.047)$, and $b = 0.6609–0.4767 \cdot \sin(w_s - 1.047)$. For other inclined surfaces of the girder, irradiation was estimated according to the location and orientation of the girder, the geometry and shadow of the girder, and the position of the sun. The specific calculation procedures are outlined in Duffie and Beckman [9].

Variations in the air temperature were calculated using the sinusoidal Kreith and Kreider equation [10]:

$$T_{air}(t) = \frac{1}{2}(T_{max} + T_{min}) - \frac{1}{2}(T_{max} - T_{min}) \cdot \sin\left[(t-9)\frac{\pi}{12}\right] \tag{2}$$

in which $T_{air}(t)$ is the air temperature as a function of time t, and T_{max} and T_{min} are the daily maximum and minimum air temperatures, respectively. In the calculations, the lengths of the 21st of March, June, September, and December represented the length of the days in each season.

With the defined seasonal environmental conditions, a two-dimensional heat transfer analysis was conducted on four AASHTO-PCI standard girder sections: Type-I, Type-IV, Type-V, and BT-1600 [2]. The heat transfer mechanisms involved in this study are heat irradiation from the sun, heat radiation to the surroundings, heat convection between the surroundings and the concrete surface, and heat conduction in the concrete. In the calculation of heat gain from the sun and heat loss to the surroundings, the value of solar absorptivity and surface emissivity of concrete was selected to be 0.50 and 0.85, respectively [11]. The thermal conductivity and specific heat of concrete, which defines the heat flow within the body of the concrete girder, were taken as 1.50 W/m K and 1000 J/kg K, respectively, based on a previous study on the temperature prediction of concrete pavement [12].

The influence of changes in the girder orientations on temperature distributions was also evaluated for east–west (E–W), south–north (S–N), southwest–northeast (SW–NE), and southeast–northwest (SE–NW) orientations. The largest vertical thermal gradients, calculated from the largest temperature difference between the highest and lowest temperatures along the depth of the sections, were found in the summer and in the E–W orientation. The largest lateral thermal gradients across the middle of the top flange, the web, and the bottom flange were found in the E–W orientation in the winter because of the greater exposure of the vertical surfaces of the girder to the sun in the E–W orientation. Among the four sections, the deeper and wider Type-V and BT-1600 sections exhibited larger vertical and lateral thermal gradients. The largest vertical thermal gradients in the summer were 26 °C in the Type-V section and 25 °C in the BT-1600 section. The largest lateral thermal gradients of the Type-V and BT-1600 sections in the winter were about 20 °C in the top flange, 15 °C in the web, and 25 °C in the bottom flange. Thus, for the BT-1600 girder in an E–W orientation, the thermal loads in this study were determined from the summer and winter environmental conditions in Atlanta.

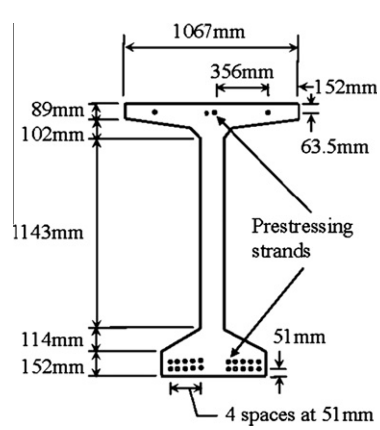

Fig. 2. Arrangement of the prestressing strands in the BT-1600.