Structures 8 (2016) 25–34

Contents lists available at ScienceDirect

Structures

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

Effect of Inconsistent Diaphragms on Exterior Girder Rotation During Overhang Deck Construction

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ARTICLE INFO

Article history:
Received 12 May 2016
Received in revised form 13 July 2016
Accepted 3 August 2016
Available online 5 August 2016

Keywords:
Deck overhang
Exterior girder rotation
Screed machine
Non-skewed bridge
Steel girder
Asymmetric diaphragm

ABSTRACT

The construction of bridge deck overhangs results in unbalanced eccentric loads acting on exterior girders which can cause rotation and increased stresses not accounted for during design. Permanent diaphragms and temporary bracing in bridge exterior girder lines or panels are used to resist these loads and subsequent transverse rotation of the exterior girders. The addition of extra diaphragms in the exterior panels is one potential alternative to temporary bracing which is not always effective. In this paper, a unique steel plate girder bridge in the state of Illinois with extra diaphragms in one exterior bay was instrumented with tilt sensors and strain gages to monitor transverse rotations and strains due to unbalanced loads occurring during construction. Two types of rotations were recorded; maximum and residual rotations. The extra diaphragms were included in the design of this bridge on only one side of the bridge to carry utility lines. The full bridge was modeled using the commercial finite element analysis software ABAQUS and the model was validated using field data. As expected, diaphragm spacing was found to have a high impact on exterior girder rotations that occur during bridge deck construction. The maximum obtained finite element rotation was 0.47° which occurred at mid span and on the bridge deck side that does not have extra diaphragms. Field residual rotations were found higher (approximate 50% on average) than rotation determined from the finite element analysis. These extra stable rotations were seen in the exterior girders and was a result of permanent deformation occurring when the finishing screed passed by the section under consideration.

1. Introduction

Bridge engineers generally use the fewest number of steel girders possible across the roadway width to reduce construction costs. In nearly every case, bridge deck extends past the exterior girders to increase the effective width of the deck. The extended width or deck overhang is shown in Fig. 1. During construction, loads from the plastic concrete and construction equipment on the overhang deck can cause excessive exterior girder rotation leading to a loss of deck thickness as well as instabilities during construction, to name a few.

The overhang deck formwork is supported by steel brackets resting against the exterior girders at a spacing of 120 cm (4 ft) to 180 cm (6 ft) over the full length of the bridge (shown in Fig. 2). The main function of these brackets is to transfer the overhang construction loads to the exterior girders. If the girders are not properly braced, these loads can lead to changes in deck thickness as well as local and global instabilities [1]. Steel plate girders with slender webs subjected to axial loads are inherently susceptible to instability or buckling [2,3] making local instabilities a major concern for plate girder bridges subject to additional eccentric loads [4,5,6,7]. On the other hand, global instability is a significant issue for concrete girders where their rotational stiffness leads to rigid body rotation [8,9]. There have been several studies to evaluate commercially available overhang brackets and hangers to limit rotation [10,11,12], although girder rotation continues to be a concern.

Rotations in exterior girders primarily depend on the geometric and structural properties of the plate girder [13,14,15]. Determining the transverse rotation of exterior girders and characterizing the effect of the rotation on the bridge is a crucial issue for bridge designers and construction engineers. In construction, girder rotations are affected by the bridge geometry, torsional stiffness of the girders, the lateral support system, and the connection details [16,17]. In particular, rotation (as

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http://dx.doi.org/10.1016/j.istruc.2016.08.002

Fig. 1. Overhang deck in a typical steel girder bridge.

shown in Fig. 3) primarily depends on the overhang deck width, diaphragm spacing, total construction loads acting on the deck overhang, and the effectiveness of the lateral bracing system used to prevent rotation during construction. In general, construction loads include the weight of fresh concrete, screed rails, overhang formwork, and construction live loads. It is possible to reduce the load effect by placing the screed rails directly over the exterior girders rather than placing them on the overhang formwork. However, most contractors prefer to place the rails on the overhang formwork to simplify concrete placement, consolidation and finishing [18] as shown in Fig. 4.

Increasing the width of the overhang deck results in a larger eccentricity which increases the torsional moment applied to the exterior girders. In the United States, the width of the overhang deck varies, but most states place some limit on their width. Generally, the maximum allowable overhang width is based on some combination of girder spacing, girder depth, and deck thickness. Exterior girder rotations are generally prevented through the use of temporary bracing systems that transfer the eccentric loads to the girders without inducing significant rotations. Several types of systems are available to contractors. One system used in Illinois includes No. 13 (No. 4) steel reinforcing bars placed parallel to the transverse reinforcement and connected to the top exterior girder flanges as shown in Fig. 5. These tie bars are usually placed at 120 cm (4 ft) to 180 cm (6 ft) intervals along the span of the bridge. Permanent diaphragms providing lateral stability and load transfer between girders also play a significant role in controlling exterior girder rotation. Specifically, the spacing between diaphragms (including intermediate diaphragms located between bridge bents) is a primary factor that dictates their effectiveness in resisting transverse deformation under unbalanced eccentric loads [19]. They are usually spaced 7.62 m (25 ft) apart.

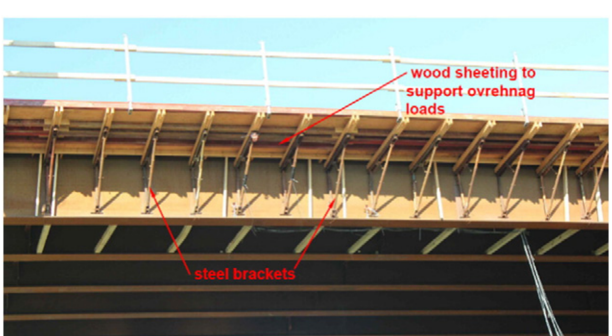

Fig. 2. Overhang deck formed by wood sheathing supported with cantilever steel brackets.

Diaphragms are traditionally placed uniformly across the width of the bridge connecting each girder. This provides continuity that is necessary to resist lateral forces (e.g., wind, earthquake, etc.) and to distribute gravity loads. However, there are some circumstances that warrant permanent diaphragms in the exterior girder panels only (rather than across the entire deck) as shown in Figs. 6 and 7 where the diaphragms are used to provide structural support for utility conduits. This inconsistent or non-continuous diaphragm pattern in exterior panels also represents a potential solution to limit exterior girder rotations. The main objective of this paper is to present the results of field-monitored rotation data for a bridge with inconsistent diaphragms in the exterior panels. Finite element analysis is performed and compared to the field data providing bridge and construction engineers with a better understanding of exterior girder rotations due to eccentric loads in the presence of additional diaphragms in exterior superstructure panels.

2. Bridge description

The bridge selected for this research is a 122 cm (48 in.) deep non-skewed plate girder bridge in the state of Illinois, USA. The continuous two-span bridge is 70 m (230 ft) in length and has integral abutments. Additional geometric details for the bridge are given in Table 1. A plan view of the bridge, girder elevations, and the diaphragm detailing are shown in Figs. 8, 9 and 10, respectively.

3. Data analysis

During construction of the deck, both inward and outward rotation of the exterior girders was measured as shown in Fig. 3. Outward girder rotations (transverse direction) are taken as positive rotation and inward rotations (transverse direction) are negative. Simple exponential smoothing (SES) was used to filter the field data (time vs. rotation) where the SES equation is given in Eq. (1).

$$\hat{x}_{j+1} = a x_j + (1-a)\hat{x}_j \quad (1)$$

where $\hat{x}_j$is the known series values for time period j, x_j is the forecast value of the variable X for time period j, $\hat{x}_{j+1}$ is the forecast value for time period and a is the smoothing constant [20].

The Statistical Package for the Social Sciences (SPSS) software is used to calculate the peak “maximum rotation” and “residual/permanent/stable rotation” of the girder as shown in Fig. 11. The “maximum rotation” of any particular section occurs when all of the construction loads [screed and finishing machine, fresh concrete (placed up to that section from one end of the deck), and other live loads] are placed at that section. The “residual/permanent/stable rotation” (shown in Fig. 11) for any section is determined after finishing placement of the deck and when all of the live loads are removed leaving only the weight of the fresh concrete. A “limit rotation” is assigned (shown in Table 1) based upon the maximum deflection ($\Delta = 4.76$ mm) at the tip of overhang deck as suggested by IDOT bridge design manual.

4. Field Data Monitoring

4.1. Instrumentation plan

Three transverse sections (S1, S2, and S3) were identified for instrumentation as shown in Fig. 12. At each of these sections, tilt sensors were placed on an exterior girder web and bottom flange and on the web of the first interior girder. Two strain gages were placed on the top transverse tie as shown in Fig. 13.

4.2. Dual-axis tilt sensor

Dual-axis (CXTLA02) tilt sensors capable of measuring rotation in the transverse and longitudinal directions were used to monitor girder