



NUMERICAL ANALYSIS OF BRIDGE GIRDERS DURING DECK CONSTRUCTION USING 7-DOF FRAME ELEMENT

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ABSTRACT

During bridge deck construction, the use of deck finishing machine and the fresh concrete often produces vertical loads and torsional moments acting on the bridge girder system. Sometimes, these loads can cause excessive deflection and twisting in the bridge girders, leading to many problems such as instability and non-uniform deck thickness during construction, as well as potential maintenance issues over the life of the bridge. Therefore, a detailed analysis is often required to evaluate the response of bridge girders under construction loads. In this study, an additional degree of freedom which represents the warping effects was added to the classic 6-DOF frame element to evaluate the torsional response of the bridge girder accurately. A finite element computer program was created in Matlab using the new 7-DOF frame element developed in this study. To evaluate the 7-DOF frame element, two Finite Element models using shell element and classic 6-DOF frame element were built in SAP2000 and compared with the model using 7-DOF frame element in term of accuracy and time consumption. The construction loads were considered moving along the bridge to simulate the whole procedure of the deck construction. The result shows that the finite element model using classic 6-DOF frame element failed to give reliable rotation values in the transverse direction since it allowed the structure members to warp freely, and the applied torque was entirely resisted by the torsional shear stress. Although both the shell element and 7-DOF frame element were able to provide accurate and reliable stress and deflection results, the model using shell element was considerably time-consuming in both modeling and computing. The findings of this study will provide designers and contractors a more efficient way to analyze the bridge girders during construction and can also be used in the future research to evaluate the lateral torsional response of bridges in the service stage.

Keywords: Bridge Girders, Deck Construction, Finite Element Analysis, Torsional Response, 7-DOF Frame Element

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1. INTRODUCTION

The bridge decks are generally designed past over the exterior girder to increase the width of deck without increasing the required number of girders [1]. The construction of the deck overhang on girder bridges is most often finished with the usage of overhang bracket and deck finishing machine [2]. Generally, the deck overhang brackets are placed along the exterior girder to support the construction loads coming from fresh concrete, screed machine, and other construction live loads. Fig. 1 shows typical construction loads acting on the bridge girders during deck placement. In most cases, these loads on the bridge girders and overhang brackets can result in torsional moments acting on the exterior girders and may lead to excessive exterior girder rotation that is not usually considered in the design of bridges [3, 4].

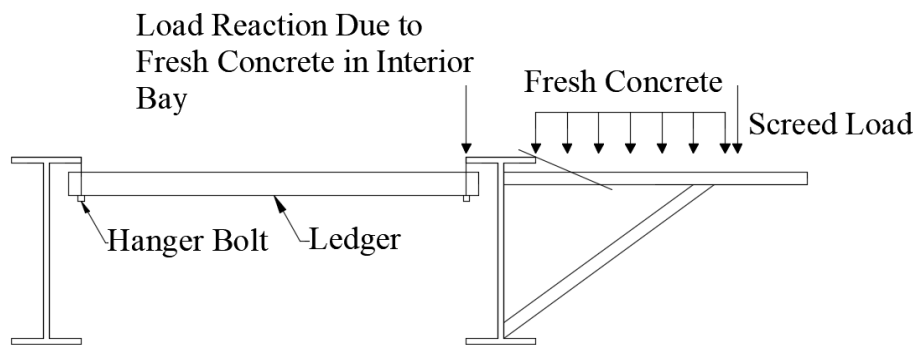


Fig. 1. Construction loads during bridge deck placement

To analyze the behaviors of girder bridges during deck construction, the most commonly used method is Finite Element Analysis (FEA). However, the classic three-dimensional frame element that is used in most commercial CAE software packages is based on St. Venant's beam theory, which allows the structural member to warp freely, and the applied torque is entirely resisted by the torsional shear stress [5]. This often leads to inaccurate results when analyzing the torsional behaviors of the bridge girder during deck construction. For the thin-wall open section beams such as I-beam, the applied torque is resisted by both St. Venant's torsional shear stress and warping torsional stress [6]. Therefore, the restrained warping effects cannot be ignored and often dominates the torsional behaviors of the bridges during the analysis.

In this study, seven degrees of freedom (7-DOF) frame element was derived and evaluated. Two finite element models using shell element and classic 3-D frame element were built in SAP2000, and the results were compared with the model using 7-DOF frame element in term of accuracy, time consumption and modeling difficulties. The result shows that the finite element model using classic three-dimensional frame element failed to give reliable results regarding the torsional behavior since it allowed the structure members to warp freely and the applied torque was entirely resisted by the torsional shear stress. Although the results from both shell element and 7-DOF frame element were able to provide accurate and reliable stress and deflection, the model using shell element was considerably time-consuming regarding modeling and computing. The finding of this study will provide engineers a more efficient way to analyze the girder bridges during deck construction and can also be used in the future research to evaluate the lateral torsional response of bridges in the service stage.

2. 7. DOF FRAME ELEMENT

According to Euler-Bernoulli beam theory, it is assumed that the cross-section perpendicular to the neutral axis of the beam remains perpendicular to the neutral axis even after deformation. Euler-Bernoulli also assumes the deformations are small and the beam is linear elastic isotropic and Poisson's ratio effects are ignored [7]. Restrained warping for the torsion of beam is not included in St-Venant torsion theory. However, for thin-wall open sections such as I-beam, restrained warping is often dominant. In this study, the beam warping theory was applied during the derivation of the stiffness matrix. Fig. 2 and Fig. 3. show the comparison between the classic 3-D beam element and 7 DOF beam element. One additional degree of freedom was added to including the effects of warping.

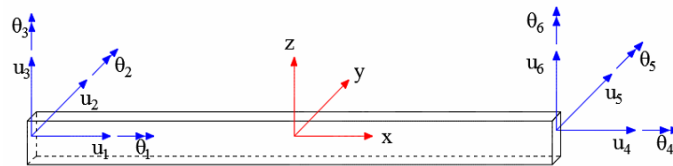


Fig. 2. Classic 3-D Frame Element

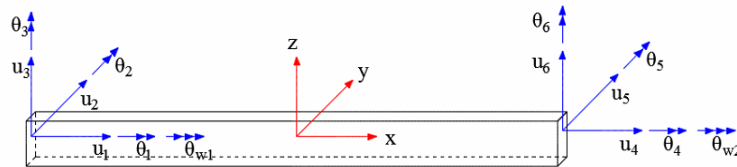


Fig. 3. 7-DOF Frame Element

2.1. Governing Equation

The relation between the axial deformation and force can be described using equation 1.

$$\frac{du_x}{dx} = \frac{F}{EA} \quad 1$$

where F is applied axial force, E is elastic modulus, and A is the area of the cross-section.

In the Euler-Bernoulli beam theory, the vertical and transverse deflection of the beam is governed by the following equations.

$$\frac{d^2u_z}{dx^2} = \frac{M_y}{EI_y} \quad 2$$

$$\frac{d^2u_y}{dx^2} = \frac{M_z}{EI_z} \quad 3$$

Where M is applied moment, I is the moment of inertia of the cross-section.

The effect of warping restraint on the torsional stiffness depends upon the amount of resistance that can be mobilized at the beam ends [8]. The warping resistance is a function of the cross-sectional dimensions, the length of the beam and the joint details at the ends of the beam. Thus, in steel beam a partial warping restraint condition may arise at the ends depending upon the joint details. The relation can be described as equation 4.

$$GJ \frac{d\theta_x}{dx} - EI_w \frac{d^3\theta_x}{dx^3} = T \quad 4$$

Where T is the applied torque, G is the modulus of rigidity, J is torsional constant, and I_w is the warping constant.

2.2. Shape Function

Shape functions are required to approximate the quantities between nodes in the beam and can be assumed to interpolate between nodes and to discretize continuous quantities to nodal degree of freedom [9]. In this study, linear functions were used to approximate the axial deformation, while cubic polynomials were used for deflections perpendicular to the beam. The deformation due to warping torsion was also approximated as cubic polynomials.

2.3. Total Potential Energy

When external forces are applied to a beam, the beam deforms. The external forces perform work and the energy that is stored in the beam in the form of stress and elastic deformation. In conformance with the law of conservation of energy, the work done in the small movements of the external forces must be equal to the potential energy stored in the beam. The total potential energy of an elastic body can be defined using equation 5.

$$\Pi = U - W \quad 5$$

Where U is the strain energy, W is the potential energy of loadings.

Therefore, the total potential energy can be written using equation 6. for the 7 DOF beam element.

$$\begin{aligned} \Pi = & \frac{EA}{2} \int_0^L \left(\frac{du_x}{dx} \right)^2 dx + \frac{EI_z}{2} \int_0^L \left(\frac{du_y}{dx} \right)^2 dx + \frac{EI_y}{2} \int_0^L \left(\frac{du_z}{dx} \right)^2 dx \\ & + \frac{GJ}{2} \int_0^L \left(\frac{d\theta_x}{dx} \right)^2 dx - \frac{EI_w}{2} \int_0^L \left(\frac{d^3\theta_x}{dx^3} \right)^2 dx \end{aligned} \quad 6$$

2.4. Element Stiffness Matrix

For conservative structural systems, the kinematically admissible deformations are corresponding to the equilibrium state extremize the total potential energy [10]. The equilibrium state is stable if the extremum is a minimum. Therefore, the Minimum Potential Energy (MPE) can be used to find the relation between the applied force and deformation, which generates the stiffness matrix. The MPE for the 7 DOF beam system can be described using equation 7.

$$\frac{\partial \Pi}{\partial U} = 0 \quad 7$$

By solving the MPE, the relation between the applied force and displacement can be written as equation 8.

$$[F] = [K^e][u] \quad 8$$

$[K^e]$ is the element stiffness matrix which is a 14 by 14 symmetric square matrix.

3. FINITE ELEMENT ANALYSIS OF A STEEL GIRDER BRIDGE IN ILLINOIS

3.1. Description of the Bridge

A bridge located in the state of Illinois was selected for the Finite Element Analysis. The bridge consists of three W30X124 wide flange girders spacing at 84 inches and compositely connected to an 8 inches thick concrete deck slab. The bridge has 3.8 degrees of skewness and has three spans of 51 ft, 81 ft and 51 ft. Also, C12X30 diaphragms are used in this bridge as the lateral bracing system. Fig. 4. shows the general layout of the bridge configuration.

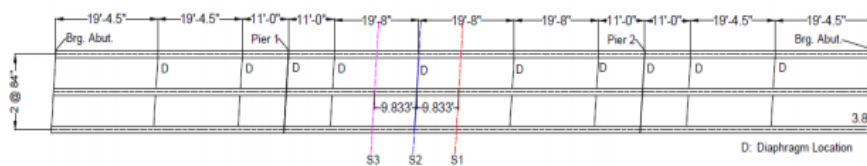


Fig. 4. The general layout of the bridge

3.2. Finite Element Models

In this study, the finite element models using shell element and classic frame element were built using SAP2000 in order to evaluate the 7-DOF frame element. As shown in Figure 5(a), for the model using shell element, three-dimensional shell elements were used to create the girder flanges, webs, and diaphragms, while frame elements were used for the brackets and bracing systems. Figure 5(b) shows the model using classic frame element in SAP2000. The bridge components including girders and diaphragms were modeled using classic frame element. The 7-DOF frame element finite element model was created using MATLAB, as shown in Figure 5(c). Loads in all the models were simplified to represent actual bridge loads including the fresh concrete weight and the finishing machine.

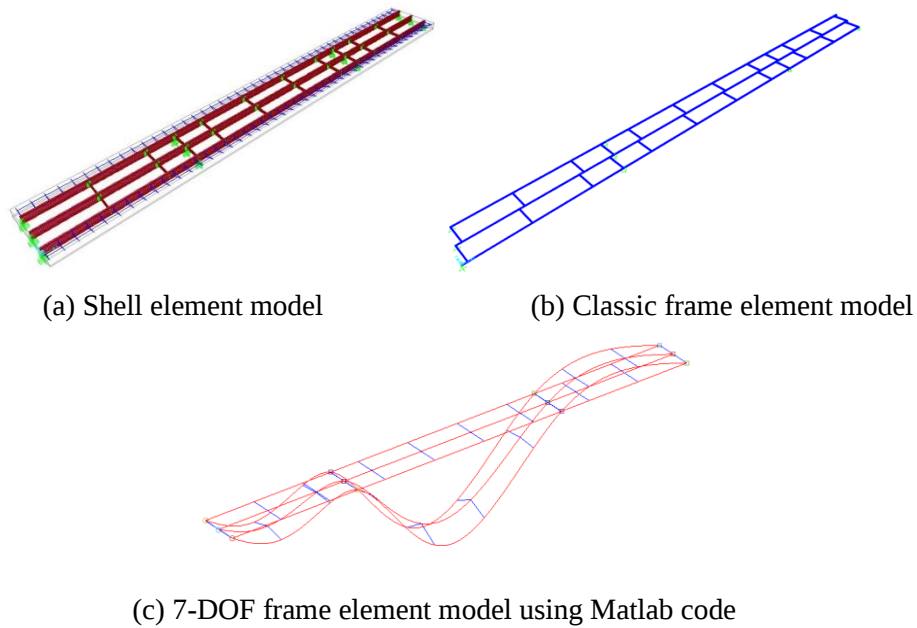


Fig. 5. Finite element models

3.3. Results

The results from three finite element models were compared when the screed machine located at the middle of the second span where the maximum exterior girder rotation usually occurred. As shown in Fig. 6. and Fig. 7., the vertical deflections and stress along the bridge exterior girder are very similar for all three models.

However, regarding torsional behaviors of the girder, the finite element model using classic beam elements, which gave almost three times larger rotation values, tend to underestimate the torsional stiffness of the girder (shown in Figure 8). On the other side, the 7-DOF beam element shows results really close to shell element, which can be considered as the contrast method. Additionally, the computational and modeling effort of the 7-DOF beam element is very similar to the classic beam element and much lesser than shell element.

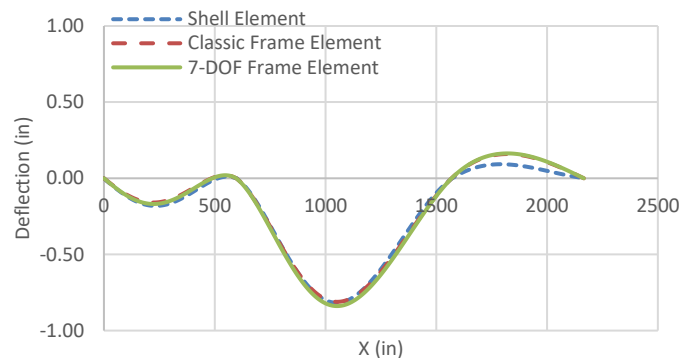


Fig. 6. Comparison of vertical deflection among three FE models

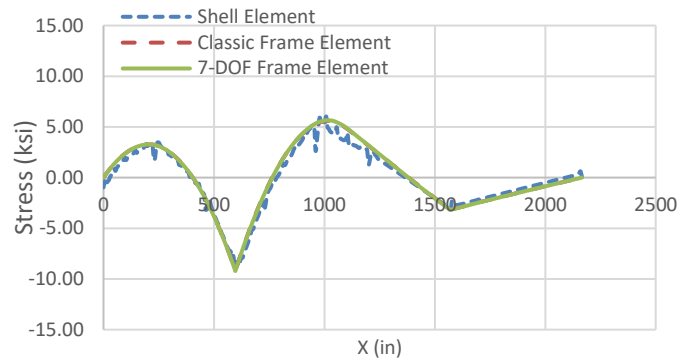


Fig. 7. Comparison of stress among three FE models

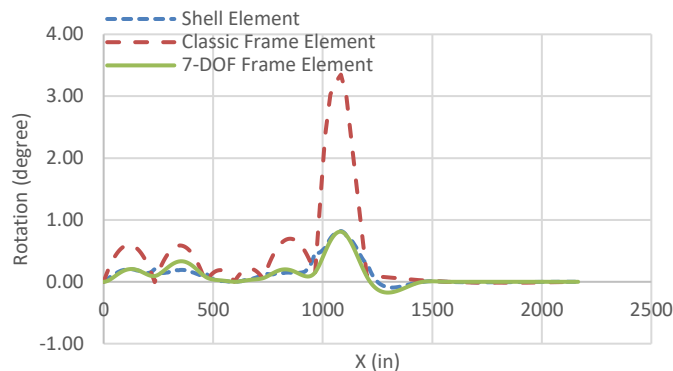


Fig. 8. Comparison of girder rotation among three FE models

4. CONCLUSION

The 7-DOF frame element was evaluated for analyzing girder bridges in this study. Three different finite element models using shell element, classic three-dimensional frame element as well as 7-DOF frame element were established and the results from each model were compared to estimate the accuracy of the 7-DOF frame element.

The results indicate that all three element types give very close values in stress and vertical deflection. However, when analyzing the torsional behaviors of the girder, the classic frame element fails to provide reliable results since the classic frame element tends to underestimate the girder's stiffness. The finite element models using 7-DOF frame and shell elements provide similar rotation values. Also, the computational and modeling efforts of the 7-DOF frame element are much less than the shell element. Therefore, the finite element analysis using the 7-DOF frame element can be considered a more efficient and accurate method in evaluating the behavior of girder bridges during deck construction.

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