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Investigation of free vibration and ultimate behavior of composite twin-box girder bridges

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ABSTRACT

Multi spine composite concrete-deck steel-box girder bridges became a very popular choice in highway bridges due to their high torsional and wraping stiffness as well as for economic and aesthetic reasons. This study presents an experimental investigation on both elastic and ultimate behavior of composite box girder bridges in order to study the effect of internal cross bracing between box girders along with the curvature effect at different loading stages. Three composite concrete deck-steel simply-supported twin-box bridge models, two curved and one straight, were fabricated, and tested. First, the response of each model was monitored under free-vibration excitation, then an eccentric loading was applied and the corresponding deflections were recorded in the elastic range. Finally, the bridge models were tested up to collapse. The structural behavior of the three bridge models was compared at the three loading stages. It was noticed that the presence of an external cross bracing system between the steel boxes had an insignificant effect on the developed deflection and the fundamental natural frequency in the elastic range of loading. On the other hand, these external bracings assisted in decreasing the developed deflection approaching failure and in increasing the load carrying capacity by about 8.9%. In addition, the external bracing ensured a better distribution of the stresses under ultimate loading conditions. Moreover, the experimental findings were verified numerically using finite element modeling. A good agreement was noticed to exist between the experimental findings and the numerical results.

1. Introduction

Horizontally curved bridges have become more commonly used, especially where tight geometric restrictions are encountered. Curved bridges allow smooth traffic flow and create a smooth directional transition at interchanges. Because of the well-known structural advantages of box girder bridges, including a shallower depth of cross-section, and significant longitudinal bending and torsional stiffness, they have become a popular solution for medium- and long-span bridges in modern highways in large urban areas and even in railway bridges. Also, box girder bridges have more resistance to vibration effects caused by live load than I-girder bridges. In addition to their obvious structural benefits, the surface inside box girder bridges is closed from the outside environment. The required utilities can be placed inside the boxes which is aesthetically more pleasing and at the same time this minimizes the surface area vulnerable to environmental conditions compared to an open-section bridge. Maintenance costs are also minimized throughout the life of the structure.

Various experimental studies have been performed on the elastic response of box girder bridges in order to verify and validate the accuracy of computer programs and available methods adopted to investigate the structural behavior of box girder bridges. Kissane and Beal [1] performed a test on a horizontally curved composite concrete deck-steel bridge located on the Avoca-Bath section of the Southern Tier Expressway. The bridge was a three-spine two-span continuous box bridge. One year later, a similar testing on a three-span continuous curved composite concrete deck-steel twin-spine box girder bridge located in the I-695 and I-83 interchange near Baltimore had been conducted [2]. Evans and Rifaie [3] performed experimental work on eighteen simply-supported single-cell models of different curvatures to validate results obtained from the finite-element method. Furthermore, an experimental work was conducted [4,5] on a series of aluminum small scale straight, skewed, and curved four-cell box girder bridge models. By applying a single point load at different locations along the span, these models were tested elastically both with and without a mid-span radial diaphragm. Brennan and Mandel [6] tested elastically small-scale horizontally curved I-girder and composite concrete deck-steel multi-spine bridge models. Data from this work were collected for possible future analysis and comparisons. Using this data and based on the folded plate method, finite-strip method, and finite-element method, Seible

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and Scordelis [7] summarized five representative bridge models to verify the elastic solutions. A curved two-span continuous, single cell, laboratory scale model had been tested [8] under point load in different locations at the mid-span cross-section. Heins et al. [9] performed elastic testing on a small scale curved three-spine box girder bridge model made of plexiglass in order to examine the applicability of the slope deflection theory that is based on Vlasov's thin-walled beam theory, which consider neither cross-section distortion nor warping.

An investigation on two, single-cell, plexiglass models having high curvature had been conducted in order to investigate the effects of intermediate diaphragms and the adequacy of the three-dimensional finite-element modeling of curved single-cell structures [10]. Xi-jin and De-Rong [11] tested elastically a plexiglass model of a three span continuous curved, two-cell, box girder bridge model to verify the accuracy of the finite-strip method in predicating the behavior of curved multi-cell bridges. Siddiqui and Ng [12] tested elastically two straight plexiglass, single cell, box girder bridge models to determine the effect of transverse diaphragms on the behavior of the box section under concentric and eccentric point loading. In addition, static and dynamic tests were performed [13] on two 1/7 scale model bridges. Both of these models were simply supported prestressed concrete bridges; the first had one-cell and the second had two-cells. The main purpose of that work was to provide experimental data on the linear and non-linear response of concrete box girder bridges at different levels of concrete cracking damage. Ng et al. [14] conducted an experimental study on a 1/24 linear scale model of the Cyrville Road bridge overpassing the Queensway, east of Ottawa. The model was a curved four-cell box girder bridge made of concrete and aluminum. The model was continuous over the central support and was tested elastically under various OHBD truck loading conditions.

In all previously mentioned experimental and theoretical work done on box girder bridges, only a few studies dealt with the non-linear behavior to collapse as well as the local buckling of individual steel plates of straight and curved box girder bridges. Heins and Humphreys [15] performed up to failure testing on a series of box beam models; the models were loaded using a combination of increasing torsional and bending forces. These models were composed of top steel flanges, steel webs, a steel bottom flange, and cross-bracings. Only some of the models had a concrete deck slab. Results of this work were used to verify the classical torsional theory in the elastic range and to develop a non-dimensional equation to expedite the load factor design of curved steel box girders. A numerical method and a computer program had been developed [7] to trace the nonlinear response of multi-cell reinforced concrete box girder bridges under increasing static loading. The results from that technique compared well with results from a two-span, four-cell, reinforced concrete box girder bridge, tested to collapse [16]. Other researchers tested to complete collapse a 1:12 scale prestressed concrete bifurcated box girder bridge model [17,18]. The model represented a four-lane carriageway bifurcating into three- and two-lane spans, and was of typical single and two-cell box girder construction, incorporating large scale cantilevers. The bridge, highly curved in plan, was continuous over the central supports and torsionally restrained at the three outer supports. A similar study was conducted by [19], but on a curved composite concrete-deck steel multi-spine box girder assemblage.

Another researchers combined the Bazant-El Nimeiri, and Zhang-Lyons models to develop a curved non-prismatic thin-walled single-cell box beam element for nonlinear analysis of reinforced and prestressed concrete box girder bridges [20,21]. Mari et al. [22] developed a straight box-beam of non-deformable cross-section composed of concrete panels with steel layers to model curved prestressed box girder bridges. A finite-element computer program had been constructed [23] to predict the materially non-linear behavior up to collapse of structures made of plain concrete, reinforced concrete, prestressed concrete, steel, and composite concrete-steel. A 1/7 Scale models of single-cell and two-cell prestressed concrete box girder bridge models, tested to destruction by [24] were analyzed using the proposed nonlinear technique. A similar mathematical model had been developed [25] for nonlinear analysis of reinforced and concrete structures. Ng et al. [26] developed similar finite-element program to trace the nonlinear response of only reinforced concrete structures. A two-span, four-cell, reinforced concrete box girder bridge, previously tested by [16], was used to compare with this analysis.

Soliman and Elmekaway [27] conducted a nonlinear finite-element analysis to investigate the effect of a bottom slab provided near the intermediate support region on the deformation behavior of reinforced concrete girder type bridges. The theoretical study was extended [28] using a nonlinear finite-element technique to examine the effect of the intermediate diaphragms and end-diaphragms on the behavior of short, medium, and long span, single-cell, box girder bridges. Yabuki et al. [29] presented a numerical method for predicting the influence of local buckling in component plates and the distortional phenomenon on the nonlinear behavior and ultimate strength of thin-walled, welded steel box girders curved in plan and stiffened by intermediate diaphragms. Few researchers investigated the behavior of box girder at construction stage [30]. Other researchers investigated the load distribution of truck loading among box girders [31–35]. Another researches concerned with the design aspects of box girders [36–41].

During lifting and when the box girders are temporarily unbraced, lateral deflections and twist are large. Top lateral bracing to the top flanges of the box section before deck concrete hardening limits box twist, warping moments in the top steel flanges of the box and excessive deflection during construction [42]. Once the concrete deck has hardened, it acts as the top flange of the box section and is capable of transferring the shear. Since the deck is usually stiffer than the bracing, the bracing is ineffective [43]. In addition, the shear stiffness of the top lateral bracing is very small compared to the reinforced concrete deck slab between top steel flanges in the composite box girder. In summary, this study ignored the presence of the top lateral bracing to the top steel flanges as it is limited to the behavior of the composite box girder at service as well as at the ultimate loading stage, rather than behavior of the non-composite box girder at construction stage.

On the basis of the literature review on curved bridges, experimental test data up to complete collapse on curved composite box girder bridges is as yet unavailable. The current experimental work aimed to verify experimentally the effect of cross bracings along with the curvature on both free vibration behavior in addition to the ultimate behavior of composite concrete-deck steel-box girder bridges.

2. Experimental work program

The experimental program was undertaken in order to investigate the behavior of curved and straight box girder bridges under static and free-vibration loading conditions, and the influence of curvature on the structural response. In the experimental program, bridge models were built and loaded up to failure.

2.1. Bridge models

The experimental program was carried out on three 1:10 linear-scale composite concrete deck-steel twin-box girder bridge models under free-vibration, under elastic and up-to-collapse loadings. This models tested experimentally were of 1:10 linear scale of actual bridge configuration. As such the added mass to the bridge was not considered since the tested models were for comparative study between a curved bridges system and a straight bridge system with the same mass and stiffness. All of the three models were simply-supported. Two of the models (M1 & M2) were curved in plan, while the third model (M3) was a straight bridge. In order to study the effect of the presence of cross-bracing between boxes on the structural response, the first model, M1, had five cross-bracing and top-chord systems between the radial support lines inside and between boxes, while the second