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Evaluation of a Bridge Using Simplified Finite Element Modelling

Evalutation des ponts à l'aide d'un modèle simplifié par éléments finis

Evaluation von Brücken durch vereinfachte FE-Modellierung

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SUMMARY

An experimental-numerical comparison of the forced and ambient vibrations of a multi-span composite plate-girder bridge was performed. The bridge was modelled using a finite element program at three levels of complexity, including a simple 250 degrees-of-freedom model that utilises a single beam element to represent the entire bridge cross section. Difficulties encountered in the development of the simple model are discussed. The dynamic properties predicted by the simple model were consistent with those measured on the bridge and computed using more detailed finite element models.

RÉSUMÉ

Une comparaison expérimentale et de type numérique sur les vibrations forcées et naturelles d'un pont-poutre composite à plusieurs travées a été effectué. Un programme d'élé-ments finis à trois niveaux de complexité, et un modèle simple à 250 degrés de liberté ne comprenant qu'une seule poutre comme élément pour représenter la coupe transversale du pont ont été réalisés. Les difficultés rencontrées lors du développement du modèle simplifié sont commentées. Les propriétés dynamiques prédites par le modèle simplifié se sont avérées concorder avec les propriétés mesurées sur le pont et calculées en utili-sant des modèles d'éléments finis plus détaillés.

ZUSAMMENFASSUNG

Ein experimentell-numerischer Vergleich der gezwungenen und natürlichen Schwingungen einer Plattenbalkenbrücke wurde durchgeführt. Die Brücke wurde durch ein FE-Programm auf drei Komplexitätsniveaus modelliert, insbesondere als ein einfaches Modell mit 250 Freiheitsgraden, welches einen einzelnen Balken benutzt. Die Schwierigkeiten bei der Entwicklung des einfachen Modells werden beschrieben. Die vorhergesagten dynamischen Eigenschaften stimmten sowohl mit den Messungen auf der Brücke als auch mit der Berechnung eines komplexeren FE-Modells überein.

1. INTRODUCTION

In the 1960's and 1970's over 2500 bridges were built in the U.S. with a design similar to those on Interstate 40 over the Rio Grande in Albuquerque, New Mexico, Fig. 1. Because the bridges over the Rio Grande were to be razed during the summer of 1993, the investigators were able to perform extensive dynamic testing on the bridges using both ambient and forced vibration techniques. This paper summarizes the numerical models of the bridge and compares results obtained with these models to the measured dynamic properties of the bridge. A primary purpose of the work reported herein is to determine if a very simple beam element representation of the bridge could be developed that would accurately predict the global dynamic response of the bridge. Such models would be very useful for designers because they would provide a simplified PC-based computational tool with which to examine the dynamic response of the bridges to a wide variety of load conditions. First, a brief description of the bridge and summary of experimental results is presented, followed by a summary of numerical calculations and correlations with experimental results.

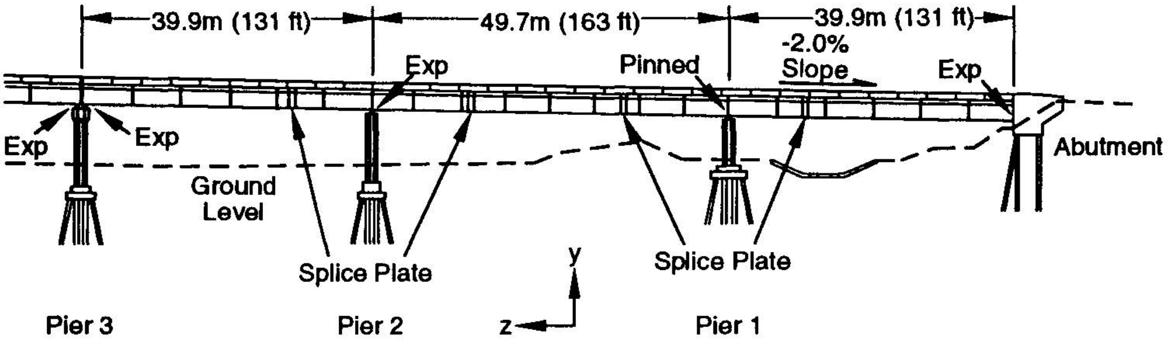

Fig. 1. I-40 Bridge Over The Rio Grande

2. DESCRIPTION OF THE I-40 BRIDGES

The existing I-40 bridge over the Rio Grande consists of twin spans made up of a concrete deck supported by two welded-steel plate girders and three steel stringers, Fig. 2. Each bridge is made up of three identical sections. All testing was performed on a single, three-span section.

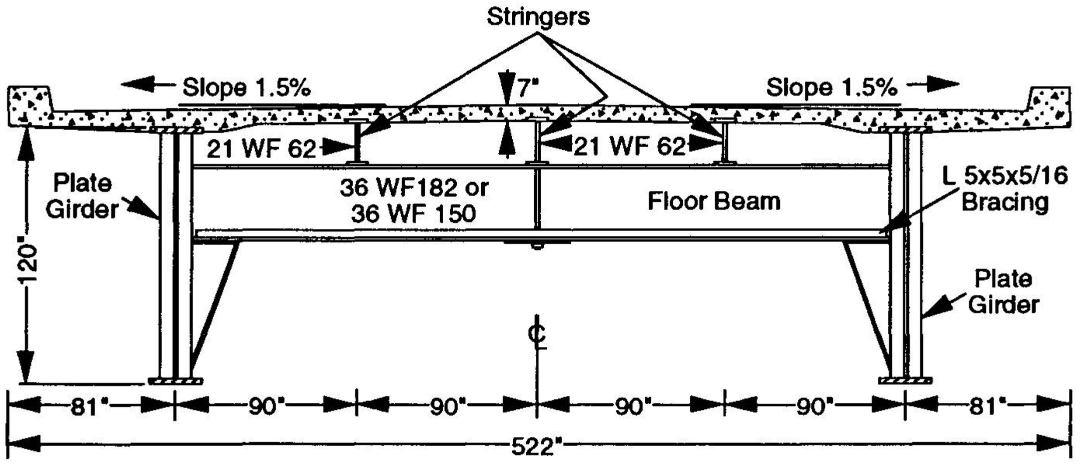

Fig. 2. I-40 Bridge Cross- Section

Drawing not to scale
1 in. = 2.54 cm

3. SUMMARY OF EXPERIMENTAL RESULTS

3.1 Ambient Vibration Testing

Ambient (traffic) vibration tests were conducted to identify the structure's resonant frequencies, modal damping, and the corresponding mode shapes. Testing was performed both with and without traffic on the tested section of the bridge. In the latter case, excitation was induced by traffic on the adjacent bridge transmitted through the ground. To circumvent the drawbacks of the methods used in previous ambient vibration tests [1], an ambient vibration system identification method [2] was applied to the measured response data. Ambient vibration from traffic was found to provide an adequate source of input for identifying the dynamic properties of the bridge. Integrated circuit piezoelectric accelerometers were used for vibration measurements. The data acquisition system, consisting of 29 input modules and a signal processing module, is described elsewhere [3].

3.2 Forced Vibration Testing

A series of forced vibration tests was conducted on the same bridge section using a hydraulic actuator and large reaction mass. Traffic was removed from the bridge during testing. A random signal generator was used to produce a uniform random signal. Force input to the bridge was determined using an accelerometer mounted on the reaction mass. The level of excitation during the forced test was on the same order as provided by direct traffic ambient excitation. All instrumentation used for the forced vibration test was identical to that used for the ambient vibration tests.

3.3 Data Reduction

Resonant frequencies, mode shapes, and modal damping values were determined by fitting analytical models to the measured frequency response function data using a commercial curve fitting algorithm. Dynamic properties measured during the forced vibration test fall within the range of those measured during the various ambient vibration tests.

4. DETAILED FINITE ELEMENT ANALYSIS

Two detailed finite element models of the bridge were developed. The first model utilizes eight-node shell elements to model the web of the plate girder and the concrete deck. Three-node beam elements were used to model the stringers, floor beam, and flanges of the plate girder. Twenty-node continuum elements were used to model the concrete piers. This model had approximately 4500 degrees of freedom describing the bridge structure above the pier. Fixed boundary conditions were specified at the base of the piers. No attempt was made to model the soil medium underneath these piers.

A second more detailed model was constructed, similar to the first, but with a more refined mesh. This more detailed model uses approximately 25,000 degrees of freedom to model the bridge deck and supporting steel structure. Comparisons of modal analyses for the 25,000 and 4,500 degree-of-freedom models revealed almost identical dynamic properties, indicating convergence.

5. SIMPLIFIED FINITE ELEMENT MODEL

When compared with experimental results (subsequently discussed), it is evident that the detailed finite element models of the I-40 Bridge described in the previous section provide an accurate model for calculating the dynamic response of the bridge. However, the detailed models suffer from complexity and size, as structural elements are intricately modeled using shell elements. A more simplified and practical model using a single beam element to represent the cross-section of the bridge would be desirable. However, certain confounding factors make the representation of the bridge by simple beam elements somewhat difficult. These factors include the composite (steel and concrete) nature of the bridge construction, the presence of but a single axis of symmetry in the cross section, and the dynamic nature of the bridge response. Implications of the above factors are that some flexural and torsional modes of response will be coupled[4] and that determination of the shear center and the torsional constant of a non-circular composite cross section will be required.

The ABAQUS Finite Element Program [5] was selected for both the refined shell element models of the I-40 Bridge as well as for the simplified beam element model. The program is representative of a class of high quality general purpose finite element packages commercially available to the technical community. Therefore, the development which follows regarding consistent input for the simplified beam model is representative of the input considerations needed for most other finite element software packages as well.

5.1 Modeling Flexural Behavior

The cross-section of the I-40 bridge shown in Fig. 2 has been idealized as consisting of the following components: A concrete slab of constant thickness with a cross-sectional area equivalent to that of the actual slab shown in Fig. 2; two steel plate girders; and three steel stringers. The procedures for representing the composite bridge cross section as a simple beam for the purpose of calculating the dynamic flexural response of the beam are based on well known methods for transformation of a composite cross section into an equivalent single material [6]. An equivalent mass density of the bridge is then determined such that the transformed section will have the same mass per unit length as the original section.

5.2 Modeling Torsional Behavior

The I-40 Bridge cross section is composed of steel and concrete members. It can be shown that the total torsional stiffness of the n individual members are

$$\frac{T}{\theta} = \sum_{i=1}^{n} G_i J_i , \qquad (1)$$

where G_i and J_i are the shear modulus and torsional constant for the $i^{\underline{th}}$ material. Individual torsional constants are determined using handbook values or well-known formulas for rectangular sections.

5.3 Shear Center Location

The general problem of non-uniform torsion of open, thin-walled members composed of any number of different materials is addressed in [7]. Unfortunately, application of the method to the I-40 bridge cross section was not straight forward. Instead, the shear center for the I-40 bridge was located numerically using the ABAQUS shell model described in Section 4. The procedure used is to apply a static force to the bridge cross section using effectively a rigid link offset from the center of the concrete slab by a distance e. By calculating the rotation of the cross section about the z-axis for two different values of e, an extrapolation was made to determine the value of e that results in no net rotation of the cross section.

5.4 Modeling the Mass Distribution

For the torsional portion of the coupled beam response to be correct, the generalized torsional mass must be input properly. This implies that the mass polar moment of inertia about the center of mass must be correct. The area polar moment of inertia. I_p, in ABAQUS is internally computed from the user-supplied area moments of inertia. The quantity $\mu L I_p$, where L is the length of the beam, then provides the generalized torsional mass necessary to correctly model the torsional vibration response. A confounding factor is the area moments of inertia are input about the centroid of the cross section which, in general, is not coincident with the center of mass.

The procedure utilized is to calculate the center of mass of the composite steel/concrete beam cross section, determine the polar moments of inertia about the center of mass for both steel and concrete components in the cross section and then use the following equation to determine an equivalent mass density, μ_{eq}, for torsional vibrations,

$$\mu_{eq} = \frac{\mu_c I_{pc} + \mu_s I_{ps}}{I_{11} + I_{22}}, \qquad (2)$$

where I_{11} and I_{22} are the moments of inertia supplied to ABAQUS, μ_s is the mass density of the steel, μ_c is the mass density of concrete, I_{ps} is the polar area moment of inertia of the steel cross section about the center of mass, and I_{pc} is the polar area moment of inertia of the concrete cross section about the center of mass. Finally, the area of the equivalent beam is specified such that the mass density given by Eq. 2 produces the correct mass per unit length of bridge cross-section to model torsional and flexural behavior. Specifying the area in this manner will produce errors in the axial response of the beam, but such response is unimportant for the I-40 Bridge.

6. RESULTS AND CONCLUSIONS

Results of the finite element analyses are compared to experimental results in terms of resonant frequencies and mode shapes in Table I.

TABLE I

Comparison of Analytical and Experimental Modal Analysis Results

		Resonant Frequency (Hz)		
	Mode Type	Experimental	Detailed FEM	Simplified FEM
Mode 1	Bending	2.48	2.59	2.85
Mode 2	Torsion	2.96	2.78	3.01
Mode 3	Bending	3.50	3.71	4.28
Mode 4	Bending	4.08	4.32	5.55
Mode 5	Torsion	4.17	3.96	4.56
Mode 6	Torsion	4.63	4.50	5.11
Ave. % Diff. from experimental		--	5.08%	15.8%

Examination of the mode shapes predicted by both the detailed and simplified finite element models shows that the measured mode shapes are being accurately predicted by both numerical simulations. The detailed model accurately predicts the measured resonant frequencies with an average percent difference of 5.08% from the measured values. The larger discrepancy between the measured resonant frequencies and those calculated by the simplified model are attributed to the inability to model three dimensional features such as cross beams and the plate girder - pier supports.

The major contribution of this study is a simple 250 DOF model that uses a single beam element to represent the entire bridge cross-section. This model required the development of a method for analyzing the torsional response of an open thin-walled cross-sectional of two materials. Because the finite element code used does not allow the polar area moment of inertia to be specified explicitly, methods of calculating an equivalent mass density and cross-section area had to be developed to accurately model both the flexural and torsional response. Because of the limited numbers of DOFs, this type of model can be exercised extensively on a PC (typical of the computing environment at most smaller consulting engineering firms) to study the response of the bridge to time-varying inputs such as seismic or wind loading. The mode shapes predicted by this simple model were consistent with those measured on the bridge. Resonant frequencies, however, show more error because of the inability to model certain three dimensional effects associated with the supports and with out-of-plane structural members. Further refinements to simplify the modeling of these three dimensional effects are needed. The location of the shear center and specification of cross-section warping properties are important input parameters for modeling the dynamic response of a cross-section where the centroid, center of mass, and shear center are not coincident, hence further work is needed to develop a simple method for approximating these properties. Work in both these areas is currently being pursued at Los Alamos National Laboratory.

7. ACKNOWLEDGMENTS

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