Curvature Matters: Unraveling the Earthquake Response of Cellular Bridges

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Abstract

Subject of the Study: This research addresses the seismic analysis of curved bridges with cellular decks, which exhibit complex dynamic behavior. Traditional Finite Element Method (FEM) models are computationally expensive, creating a need for efficient, simplified analytical techniques. **Objectives**: The study aims to develop and validate a simplified modeling technique, the Panel Element Method (PEM), for the efficient seismic analysis of curved cellular bridge decks. **Materials and Methods**: The proposed Panel Element (PE) models an entire plane panel of the bridge deck as a single element. The method's accuracy was verified through a comparative study with detailed FEM models in ANSYS. A program implementing the PEM algorithm analyzed various bridge configurations under earthquake excitation. **Results**: PEM proved valid for estimating earthquake response. Compared to FEM, it yielded acceptable accuracy, with errors below 12% for deflections and below 18% for moments and shear forces, even in decks with large aspect ratios. The method was effective for both free/forced vibration and seismic analysis. **Conclusions**: The Panel Element Method is a valid and efficient technique for seismic analysis of curved cellular bridges. Its primary advantage is a significant reduction in computational complexity compared to FEM, while maintaining acceptable accuracy. PEM is recommended for practical engineering use in dynamic and approximate seismic analysis.

INTRODUCTION

Curved bridges are increasingly prevalent in highway systems due to their economic, aesthetic, and space-efficient advantages in urban and mountainous terrain [1, 2]. However, their structural complexity and inherent curvature make them more vulnerable to seismic damage than straight bridges, primarily due to coupled bending-torsional responses under ground motion.

While most research has focused on static and linear dynamic analysis, a critical gap exists in efficiently identifying the seismic input parameters that most critically affect curved bridge response. Current code-prescribed methods for multiple seismic inputs are computationally intensive. This study addresses this by developing a simplified procedure for the seismic analysis of curved cellular bridges.

The objective is to analyze the bridge's response to longitudinal and transverse earthquake motions, characterized by a modified pseudo-acceleration design spectrum. The dynamic forces and moments will be determined and compared using the Finite Element Method (FEM) and the Panel Element Method (PEM), assuming linear material behavior. The findings aim to enhance the understanding of curved bridge behavior under seismic loading and contribute to more reliable design frameworks.

The cellular cross-section (Fig. 1) is often employed for its high torsional stiffness, yet current seismic design codes lack comprehensive guidance for such structures, as evidenced by significant historical damage.

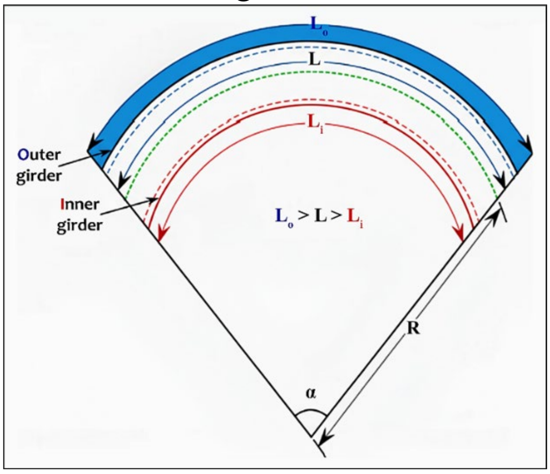

Fig. 1. Curved box-girder deck bridge. [3]

LITERATURE REVIEW

Research on the seismic behavior of curved bridges under spatially varying ground motions remains limited. Key studies have identified curvature as a critical factor influencing structural response. Early work by Sextos et al. [4] and Burdette et al. [5] established the significant impact of multi-support excitation, including wave passage effects, on curved bridges, a finding later corroborated by shaking table tests.

Complementary studies have focused on the distinct mechanical behavior induced by curvature. Investigations have analyzed its effect on prestressed tendon deformation [6], live load distribution [7], and torsional mechanics [8]. Further finite element analyses have quantified the response of curved girder and box-girder bridges to various loads, examining parameters such as curvature angle and span-depth ratio [9].

Collectively, this body of literature confirms that curvature fundamentally alters a bridge's seismic and structural response, necessitating specialized analysis that accounts for both spatial ground motion variation and unique curvature-induced effects.

MATERIALS AND METHODS

This study investigates the seismic response of curved cellular bridge decks using a newly proposed Panel Element Method (PEM), validated against the conventional Finite Element Method (FEM). The research methodology involved numerical modeling and simulation of various curved box-girder bridge configurations.

Material properties were defined by an Elastic Modulus of 23.5×10^6 kN/m², a Weight Density of 24.517 kN/m³, and a Poisson's Ratio of 0.20 (Table 1).

Table 1. Material properties for MATLAB and ANSYS models

No.	Material Properties	MATLAB Values	ANSYS Values
1	Elastic Modulus (E)	23.5 x 10^6 kN/m^2	23.5 x 10^3 N/mm^2
2	Weight Density (γ)	24.517 kN/m^3	2,500 kg/m^3
3	Poisson's Ratio (υ)	0.20	0.20

The research objects were four case studies based on an existing bridge in Baghdad, incorporating single and double cells with rectangular and trapezoidal cross-sections (Fig. 2). Span lengths were 20m and 30m, with curvature angles of 20° and 30°. The bridges were modeled as linear elastic reinforced concrete structures.

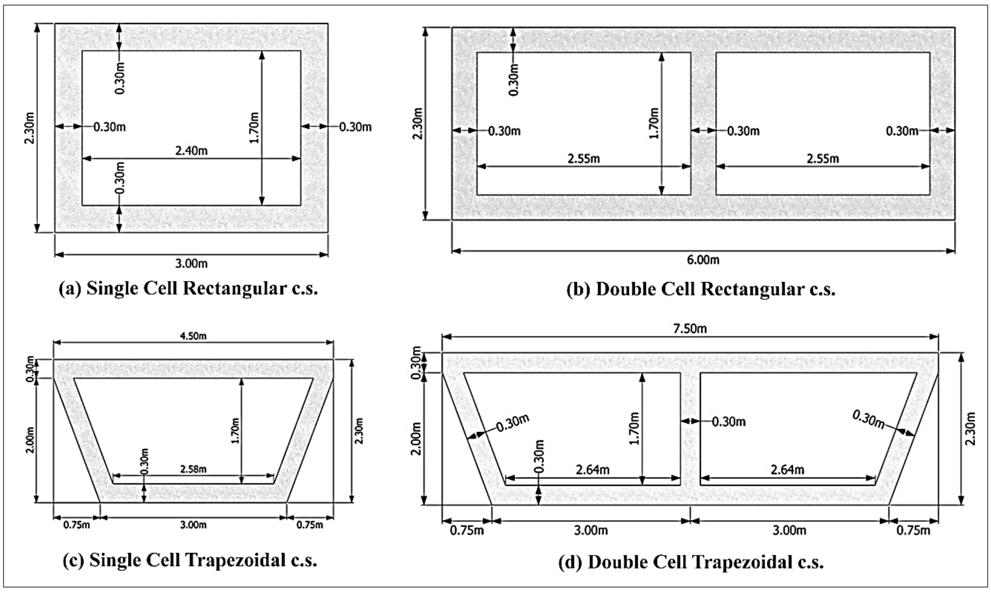

Fig. 2. Case studies of curved box-girder deck bridge types.

The core method was the PEM, which idealizes the bridge deck as an assemblage of flat plate wall panels. Each Panel Element (PE) was modeled as a space frame element, accounting for both in-plane and out-of-plane flexural and shear deformations. This method significantly reduces the number of elements and degrees of freedom compared to detailed FEM. For verification, equivalent models were created in ANSYS v12.0 using SHELL63 and BEAM4 elements.

The analysis procedure subjected the models to earthquake base excitations in horizontal (X) and vertical (Y) directions, characterized by a modified pseudo-acceleration design spectrum. The dynamic analysis employed Response Spectrum Techniques to determine maximum deflections, bending moments, and shear forces. A parametric study was conducted to evaluate the effects of the number of cells, web-to-flange thickness ratio, number of diaphragms, and live load according to Iraqi specifications.

RESEARCH RESULTS

The comparative analysis between PEM and FEM demonstrated the validity and efficiency of the proposed method. The results, summarized across multiple parametric studies, are as follows:

1. Model Validation: For both single and double-cell decks under horizontal and vertical excitation, PEM results showed strong agreement with FEM. The maximum error was less than 12% for deflections and less than 18% for moments and shear forces, even for cases with very large aspect ratios.

2. Effect of Number of Cells: The response of single and double-cell decks was accurately captured by PEM, with errors within the stated limits, confirming its applicability to different cellular configurations (Tables 2, 3).

Table 2. Maximum response of single-and-double-cell cantilever bridge deck (Base Excitation in X-direction).

Cell Type	Analysis Method	Max. Bending Moment			Max. Shear Force		Max. Deflection (mm)
		Abs. (kN.m)	Nor. to m* (m)	Nor. to m* x L	Abs. (kN)	Nor. to m*	
Single	FEM	614.742	0.244	0.012	75.672	0.030	1.273
	PEM	691.992	0.275	0.014	81.152	0.032	1.312

Double	FEM	705.600	0.510	0.026	92.369	0.067	1.639
	PEM	750.600	0.543	0.027	95.969	0.069	1.837

Table 3. Maximum response of single-and-double-cell cantilever bridge deck (Base Excitation in Y-direction).

Cell Type	Analysis Method	Max. Bending Moment		Max. Shear Force			Max. Deflection (mm)
		Abs. (kN.m)	Nor. to m* (m)	Nor. to m* x L	Abs. (kN)	Nor. to m*	
Single	FEM	956.133	0.380	0.019	315.773	0.126	4.077
	PEM	1023.383	0.407	0.020	325.925	0.130	4.369
Double	FEM	1016.064	0.735	0.037	404.571	0.293	5.535
	PEM	1056.912	0.764	0.038	407.235	0.295	5.700

3. Effect of Web-to-Flange Thickness Ratio: The PEM reliably predicted the structural response for thickness ratios (tw/ts) varying from 0.5 to 2.0. Errors remained below 10% for deflection and 17% for moments and shear forces at the maximum ratio.

4. Effect of Number of Diaphragms: Varying the number of diaphragms from 2 to 10 had a negligible effect on deflection. PEM consistently produced accurate results across all cases, with errors not exceeding 12% in deflection and 18% in forces, proving its robustness for different diaphragm spacings (Table 4).

Table 4. Maximum response vs. ratio of (no. of diaphragms: span) of single-cell deck bridge partially restrained at supports (Base Excitation in X-direction).

No. of Diaph.	Analysis Method	Max. Bending Moment			Max. Shear Force		Max. Deflection (mm)
		Abs. (kN.m)	Nor. to m* (m)	Nor. to m* x L	Abs. (kN)	Nor. to m*	
2	FEM	3494.16	2.527	0.126	1157.76	0.837	0.931
	PEM	4109.6	2.972	0.149	1343.68	0.972	1.007
4	FEM	3229.2	2.335	0.117	1285.74	0.930	0.898
	PEM	3799.2	2.748	0.137	1507.04	1.090	0.957
6	FEM	3600	2.603	0.130	1494.36	1.081	0.980
	PEM	4022.4	2.909	0.145	1725.408	1.248	1.040

5. Effect of Live Load: Under different live load cases (lane, military tracked, military wheeled), the dynamic response predicted by PEM showed good agreement with FEM. Errors were within 10% for deflection and 16% for moments and shear forces, further validating the method (Table 5).

Table 5. Maximum response for different live load conditions on a single-cell deck bridge partially restrained at supports (Base Excitation in X-direction).

Load Case Type	Analysis Method	Max. Bending Moment			Max. Shear Force		Max. Deflection (mm)
		Abs. (kN.m)	Nor. to m* (m)	Nor. to m* x L	Abs. (kN)	Nor. to m*	
I	FEM	5210.4	3.768	0.188	958.2	0.693	1.63
	PEM	5731.8	4.145	0.207	1030.224	0.745	1.7
II	FEM	5688.12	4.114	0.206	1068.12	0.772	1.729
	PEM	6022.08	4.355	0.218	1136.16	0.822	1.766
III	FEM	6368.72	4.606	0.230	1207.44	0.873	1.898
	PEM	6915.16	5.001	0.250	1232.04	0.891	2.019

In conclusion, the PEM provides an efficient and acceptably accurate alternative to FEM for the seismic analysis of curved cellular bridges, offering a significant reduction in computational complexity while maintaining result integrity.

CONCLUSIONS

This study validated the Panel Element Method (PEM) for the earthquake response analysis of curved cellular bridges by comparing it with the Finite Element Method (FEM). Key findings are:

1. PEM accurately models the dynamic earthquake response of single- and double-cell bridge decks with a significant reduction in degrees of freedom and computational effort compared to FEM.

2. For all practical aspect ratios, PEM provides acceptable results, with errors <12% in deflection and <18% in moments and shear forces, performing best with smaller aspect ratios.

3. The number of diaphragms has a negligible influence on the moment and shear force responses of curved decks under seismic excitation.

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