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Paper No. 1309. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EARTHQUAKE-RESPONSE CHARACTERISTICS OF LONG-SPAN ARCH BRIDGES

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ABSTRACT

The seismic performance of various types of long-span arch bridges, when subjected to uniform and non-uniform seismic excitations, is evaluated to identify the dynamic and earthquake-response characteristics of these special bridge structures. The three-dimensional models used include deck-type, half-tied, and tied arch bridges, each with arch span of 440 m. Three orthogonal components of real time-history seismic records from the 1979 El Centro earthquake are applied simultaneously at the bridge supporting points. Nonlinear time-history analyses are performed on all the models, using a tangent stiffness iterative procedure. Three sources of geometric nonlinearity are considered: change of bridge geometry due to large displacements, axial force and bending moment interaction in the arch ribs, and the coupled out-of-plane deformation. A comparison is made between the linear and nonlinear analysis results, and between the response to uniform and multiple-support excitations for the various bridge models. The study concludes that multiple-support excitation considerably increases the seismic response of long-span arch bridges, and that a nonlinear dead-load analysis preceding a linear seismic analysis reduces the arch-rib stiffness, increasing the bridge seismic response. However, a nonlinear seismic analysis could reduce this increase in response, especially the displacement response, due to a re-distribution of seismic response energy among different modes.

KEYWORDS

Arch bridges; nonlinear analysis; seismic; earthquake-response; multiple-support excitation.

INTRODUCTION

Arch bridges represent one of the three major types of long-span bridges, with the other two types being suspension and cable-stayed bridges. The effective span length of an arch bridge may range from 60 m to 600 m, and several new long-span arch bridges are being built today where site conditions and alignment of approach spans may render the arch choice the most economical one. The arch is predominantly a compression structure under gravitational loads, and the arch ribs are usually shaped to support the dead load mainly by axial compression. This axial compression in long-span bridges is large enough to reduce the arch stiffness in supporting any subsequent gravitational loads. However, under the effect of seismic excitation, the arch ribs could develop forces fluctuating between tension and compression, and the variation in arch stiffness becomes very complicated. Therefore, the seismic behavior of arch bridges needs careful investigation, and a realistic analysis procedure needs to be development for accurately predicting the response of these special structures to earthquakes.

Several studies have been conducted to evaluate the seismic response of deck-type arch bridges. However, most of these studies were applied to simple two-dimensional models (Dusseau, 1985; Kuranishi and Nakajima, 1986) which could not capture the three-dimensionality and modal coupling in the arch behavior. Few investigators considered the three-dimensional behavior of deck-type arch bridges during earthquakes, but they either utilized a linear time-history analysis technique (Dusseau and Wen, 1989) or applied a uniform seismic excitation (Lee, 1990) as opposed to multiple-support excitation.

In the present study, the nonlinear behavior of three-dimensional models of deck-type, half-tied, and tied arch bridges, when subjected to uniform and multiple-support excitations is investigated. Three sources of geometric nonlinearity are considered in the analysis: (i) change of the overall bridge geometry due to large displacements; (ii) axial force and bending moment interaction in the arch ribs; and (iii) the coupled out-of-plane deformation which involves twisting and out-of-plane bending of both the arch ribs and the deck. A comparison is made between the linear and nonlinear analysis results for all three models for the uniform seismic excitation case, and the difference between the response to uniform and multiple-support excitation is examined for the deck-type and half-tied arch bridges based on nonlinear analysis procedure.

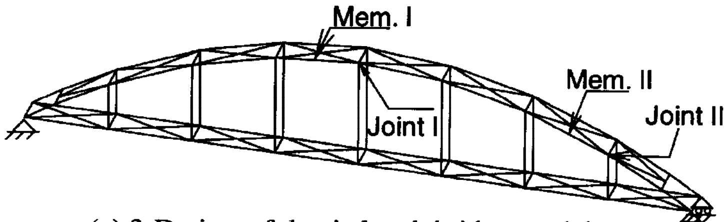
THE THREE BRIDGE MODELS

Three-dimensional finite element models of deck-type, half-tied, and tied (with bowstring girder) arch bridges were investigated, each with an arch span of 440 m. Figure 1 shows three-dimensional views of the three models and an elevation of the deck-type bridge model. Lateral bracing is provided at the deck level as well as between the arch ribs. In both the half-tied and tied arches, the deck girders are rigidly connected to the arch ribs at their intersections and the arch rib bracing ceases at a pair of portal frames as it approaches the deck level to provide the clearance required for highway traffic. In the deck-type arch bridge model, truss bracing at the arch crown is provided to help transfer the longitudinal force between the deck and arch ribs, as seen in Fig. 1(d), while lateral bracing between the deck and arch ribs, also at the crown, provides a lateral force transfer mechanism. All vertical members connecting the arch ribs and the deck girders are assumed to be link members capable of carrying only axial tension or compression. The roadway width and the distance between the arch ribs are kept constant in all 3 bridge models to a value of 20 m to accommodate 4 lanes of traffic in addition to side walks and shoulders.

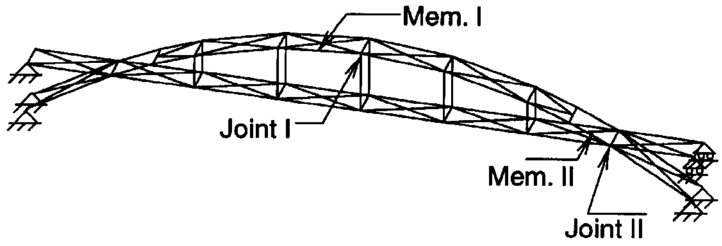
FREE VIBRATION CHARACTERISTICS

In order to evaluate the need for three-dimensional dynamic analysis, the natural modes of free vibration of all three models were plotted and examined carefully. Strong coupling between lateral and torsional motions of the arch ribs and the bridge deck within several modes of vibration was observed in all three models. Figure 2 shows selected mode shapes of the half-tied arch bridge model where such coupling was observed. Furthermore, the bridge deck lateral motion could be in phase (see mode #1) or out of phase (see mode #3) with the arch rib lateral motion. It is obvious that such out-of-plane deformation involving twisting and out-of-plane bending cannot be captured in any two-dimensional analysis, justifying the need for a true three-dimensional analysis of arch bridges.

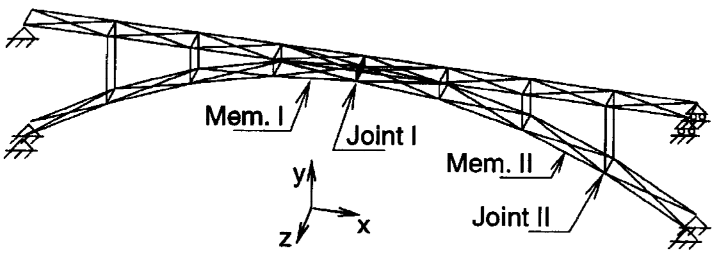
The free-vibration results for all models under investigation were based on utilizing the tangent stiffness matrix of the bridge in its dead-load deformed state obtained from a nonlinear static analysis. Due to the large axial compressive force in the arch ribs resulting from the gravitational dead load, the reduction in the bridge bending stiffness can be captured by nonlinear static dead-load analysis. The result would be a reduction in the modal frequencies of the bridge. Table 1 justifies this argument by listing the natural frequencies of the lowest 10 modes for all three bridge models, once calculated based on linear dead-load analysis (L-d.l.), and again based on nonlinear dead-load analysis (NL-d.l.) with the tangent stiffness matrix being used in the solution of the eigenvalue problem. A considerable reduction in the natural frequencies of some modes can be observed in this table, especially for the tied arch bridge model.



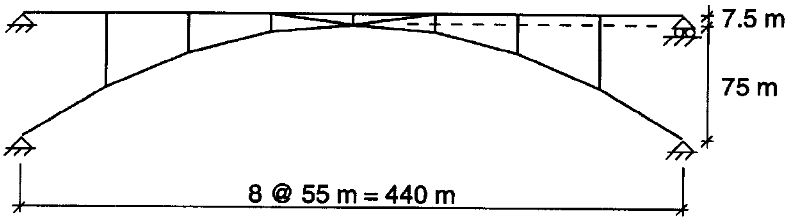
(a) 3-D view of the tied arch bridge model.



(b) 3-D view of the half-tied arch bridge model.



(c) 3-D view of the deck-type arch bridge model.



(d) Elevation of the Deck-Type Arch Bridge Model.

Fig. 1. The three analytical bridge models used in this study.

EARTHQUAKE INPUT FOR THE BRIDGE MODELS

Existing strong motion records can be used to define representative and appropriately-correlated multiple-support seismic inputs that take into account the spatial variation of ground motion. In the present study, selective ground motion records from the Imperial Valley (El Centro) Earthquake of October 15, 1979 are employed in defining the uniform and multiple-support input motions. These records were chosen in the present study because their accelerations are rich in high frequency components, and because they provide clear input ground motion due to the great magnitude of the earthquake (magnitude 6.6 on the Richter scale). Two cases of three orthogonal components of earthquake input motion acting simultaneously at the bridge supports were considered for the bridge models: (i) multiple-support seismic input, with arrays no. 5 and 6 from El Centro records chosen for input at the left and right bridge supports, respectively; and (ii) uniform seismic input with array no. 6, being the strongest of the arrays, acting at both ends of the bridge.

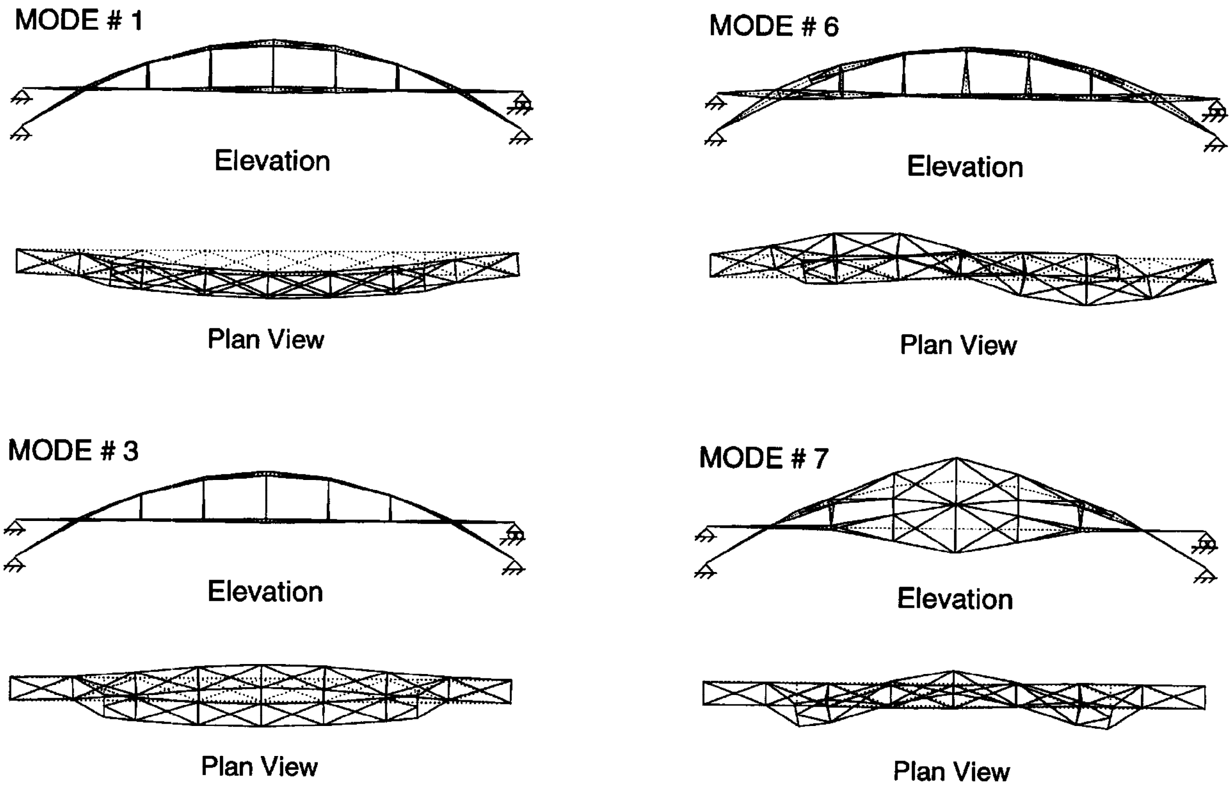


Fig. 2. Selective natural modes of free vibration of the half-tied arch bridge model.

Table 1. Natural frequencies of all models based on two different types of dead-load analyses.

Mode	Deck-Type Arch			Half-Tied Arch			Tied Arch		
No.	Freq. (Hz) from		%ge	Freq. (Hz) from		%ge	Freq. (Hz) from		%ge
	L-d.l.*	NL-d.l.*	reduc.	L-d.l.	NL-d.l.	reduc.	L-d.l.	NL-d.l.	reduc.
1	0.32	0.31	3.1	0.32	0.31	3.1	0.18	0.14	22.2
2	0.43	0.35	18.6	0.43	0.37	14.0	0.25	0.20	20.0
3	0.48	0.44	8.3	0.53	0.49	7.5	0.38	0.36	5.3
4	0.76	0.68	10.5	0.76	0.70	7.9	0.40	0.36	10.0
5	0.80	0.77	3.8	0.80	0.71	11.3	0.62	0.46	25.8
6	0.87	0.84	3.4	0.98	0.95	3.1	0.73	0.69	5.5
7	0.99	0.94	5.1	1.17	1.11	5.1	0.88	0.74	15.9
8	1.18	1.11	5.9	1.24	1.20	3.2	0.90	0.85	5.6
9	1.29	1.21	6.2	1.30	1.26	3.1	0.93	0.90	3.2
10	1.33	1.29	3.0	1.43	1.37	4.2	1.14	1.08	5.3

*L-d.l. = Linear dead load analysis, NL-d.l. = Nonlinear dead load analysis.

RESULTS OF THE SEISMIC-RESPONSE ANALYSIS

Three different types of analyses were first performed on all bridge models under the effect of uniform support excitation: (i) linear time-history seismic-response analysis, using modal superposition with 30 modes employed in the analysis, following a linear dead-load static analysis (this analysis type will be denoted L-L); (ii) linear time-history seismic-response analysis similar to the one just described in the first case, but based on the utilization of the tangent stiffness matrix of the bridge in its dead-load deformed state which is obtained from nonlinear static analysis (this type will be denoted NL-L); and (iii) nonlinear time-history seismic-response analysis, also following a nonlinear dead-load analysis, using step-by-step Wilson-θ method (Wilson *et al.*, 1973) for direct integration (this type will be called NL-NL). In the nonlinear seismic analysis, a cost-effective computational procedure was utilized to reduce the size of the matrices by transforming the analysis from the real displacement coordinate space into the modal coordinate space using the normal mode shapes of the bridge as a set of orthogonal bases. Furthermore, in the iterative procedure the modified Newton-Raphson technique was used to efficiently achieve equilibrium at the end of each time step. Finally, an analysis of the third type (NL-NL) was performed again on the deck-type and the half-tied arch bridge models for the multiple-support input case.

The formulation developed by Nazmy and Abdel-Ghaffar (1990) for the nonlinear seismic analysis of cable-stayed bridges under uniform and multiple-support excitations was further modified to accommodate the special features of arch bridges. The computer programs developed by Nazmy (1987) for cable-stayed bridges were also modified and used in the present investigation.

Comparison Among the Three Types of Analyses for the Uniform Input Case

Selected earthquake-response displacements and member forced in all three models were computed for the three different types of analyses described above using uniform earthquake excitation. The locations of joints and members selected for examination are shown in Fig. 1 for all models, while Table 2 lists the absolute maximum values of the dynamic (or vibrational) responses of the selected response quantities for all types of analyses for each model. By examining the response values in this table, it can be noticed that an increase in the response displacements and member forces has generally occurred when going from L-L to NL-L types of analyses due to the stiffness reduction of the system caused by the large axial compression in the arch ribs under the effect of dead loads (softening system). This stiffness reduction has been demonstrated earlier by the observed decrease of natural frequencies, as noticed in Table 1.

Table 2. Vibrational responses* to uniform excitation for all bridge models using three types of analyses.

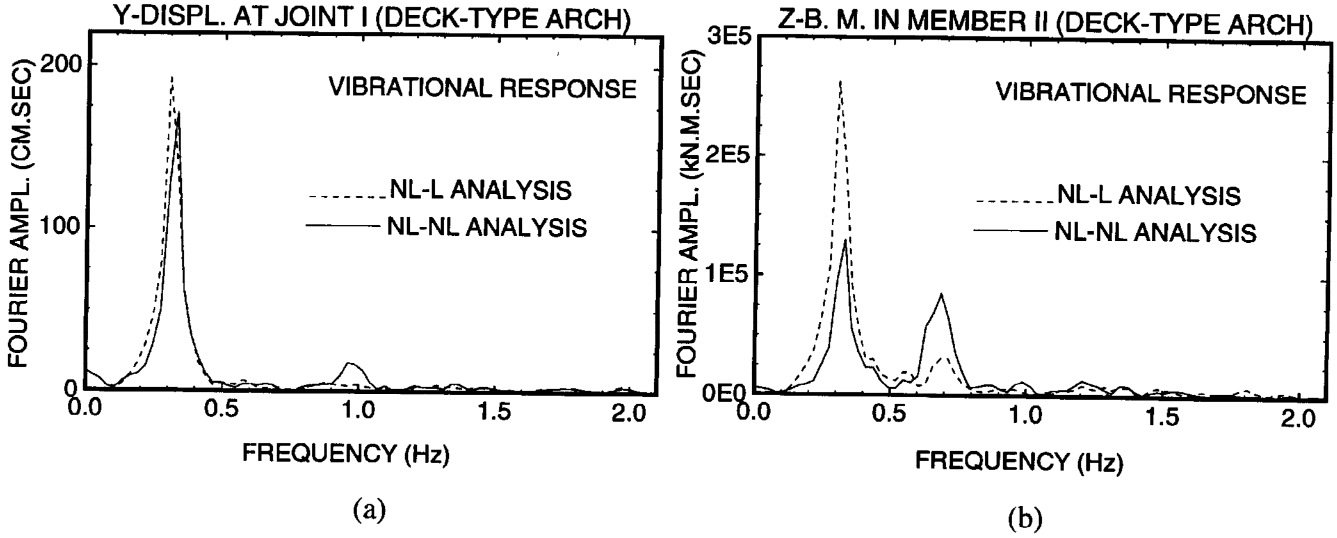
Response	Deck-Type Arch			Half-Tied Arch			Tied Arch		
Quantity	L-L	NL-L	NL-NL	L-L	NL-L	NL-NL	L-L	NL-L	NL-NL
joint I, y-displ.	29.6	31.6	23.7	23.7	28.4	27.8	34.8	36.8	30.1
joint I, z-displ.	134.7	143.8	139.0	144.7	193.5	167.3	198.0	229.8	233.7
joint II, y-displ.	17.9	22.8	16.9	13.3	13.7	14.7	26.8	47.3	20.2
mem. I, axial f.	16.3	17.9	20.6	10.4	11.8	20.0	14.6	15.6	17.4
mem. II, B.M.	47.1	54.1	30.5	66.3	61.0	73.5	20.6	25.2	43.1

*response displacements are in cm, axial forces are in MN, and bending moments are in MN-m.

The table indicates, however, that a significant reduction in the maximum response displacements has generally occurred, with few exceptions, when going from NL-L to NL-NL types of analyses. A reduction of almost 57% was observed in the Y-displacement of joint II in the tied arch bridge model, while a 25% reduction was noticed for the Y-displacement of joints I and II in the deck-type arch bridge model.

However, the axial force in member I and the vertical bending moment in member II have increased for all models with the exception of member II in the deck-type arch where its maximum bending moment decreased when going from NL-L to NL-NL analyses.

In order to explain the reduction in the seismic response displacements, when nonlinear seismic analysis is performed, the Fourier amplitude spectra of the response displacements were examined. Figure 3(a) illustrates the Fourier amplitude spectrum of the Y-displacement of joint I in the deck-type arch bridge. Two reasons for the observed increase in the response can be drawn from this Figure. First, there is a frequency shift indicating an increased stiffness of the bridge, which reduces the response displacement. This stiffness gain is in fact responsible for the observed increase of member forces under NL-NL analysis. This may be attributed to the fact that the seismic force in the arch ribs during the nonlinear seismic analysis fluctuates between tension and compression causing a continuous change (increase and decrease) in the overall bridge stiffness. However, if the maximum response displacement occurred at a moment when the force in the arch ribs was tension, then the bridge stiffness would increase as seen in this Figure. Second, the Fourier amplitude spectrum indicate that in the linear seismic analysis one mode only has dominated the response, while in the nonlinear dynamic analysis there is more modal contribution to the response and the response energy has spread over several modes with less participation from one dominating mode. The second peak in the plot occurs at frequency of 0.94 Hz, which corresponds to a coupled lateral and torsional mode. This mode does not contribute much to the vertical displacement of joint I.



(a)

(b)

Fig. 3. Fourier amplitude spectra of the response of the deck-type arch bridge to uniform excitation.

The reduction of the bending moment in member II of the deck-type arch can also be explained by examining its Fourier amplitude spectrum depicted in Fig. 3(b), where a re-distribution of the response energy over a larger number of modes can be noticed clearly.

These results indicate that strong nonlinearity does exist in the seismic behavior of this type of bridge structures, and that both nonlinear static and nonlinear dynamic analyses are necessary for correctly evaluating the seismic response of long-span arch bridges.

Comparison between the Response to Uniform and Multiple-Support Excitations:

For long-span bridges, the assumption of uniform seismic excitation at the supporting points may not be realistic. In this part of the study, a comparison is made between the responses to uniform and multiple-support excitations for both the deck-type and the half-tied arch bridge models using NL-NL analysis type.

The total nodal displacements are decomposed into quasi-static displacements and vibrational (or relative) displacements. The quasi-static displacement is caused by the nonuniform motion of the supporting points at any time instant. For the uniform input case, the quasi-static displacement at any point on the bridge will always be the same as the support displacements, resulting in zero quasi-static member forces.

Figure 4 shows the above-described comparison for the Y-displacement of joint I and the axial force in member I of the deck-type and half-tied arch bridge models. Each graph in this figure shows the vibrational and the total (vibrational plus quasi-static) responses. It is evident from this figure that multiple-support excitation has a significant effect on increasing the seismic response of arch bridges by exciting more modes of vibration due to the out-of-phase motion at the supports.

CONCLUSIONS AND RECOMMENDATIONS

Based on this investigation, the following conclusions and recommendations for the seismic analysis of long-span arch bridges can be made:

1. A two-dimensional earthquake-response analysis is not adequate for any of the arch bridge types as there is strong coupling between the in-plane and out-of-plane motions of the arch ribs and the deck.
2. In order to obtain realistic earthquake-response quantities for design purposes, it is necessary to perform the analysis with three orthogonal components of earthquake motion acting simultaneously at all supporting points of the bridge.
3. For long-span arch bridges, it is essential to perform both nonlinear static and nonlinear seismic analyses in order to obtain realistic results. A nonlinear dead-load analysis reduces the arch rib stiffness resulting in a large increase in the seismic response. However, a nonlinear seismic-response analysis could reduce this increase in the response, especially the displacement response, due to re-distribution of the seismic-response energy among several modes.
4. Multiple-support excitation considerably increases the seismic response of long-span arch bridges, when compared with uniform excitation effect.

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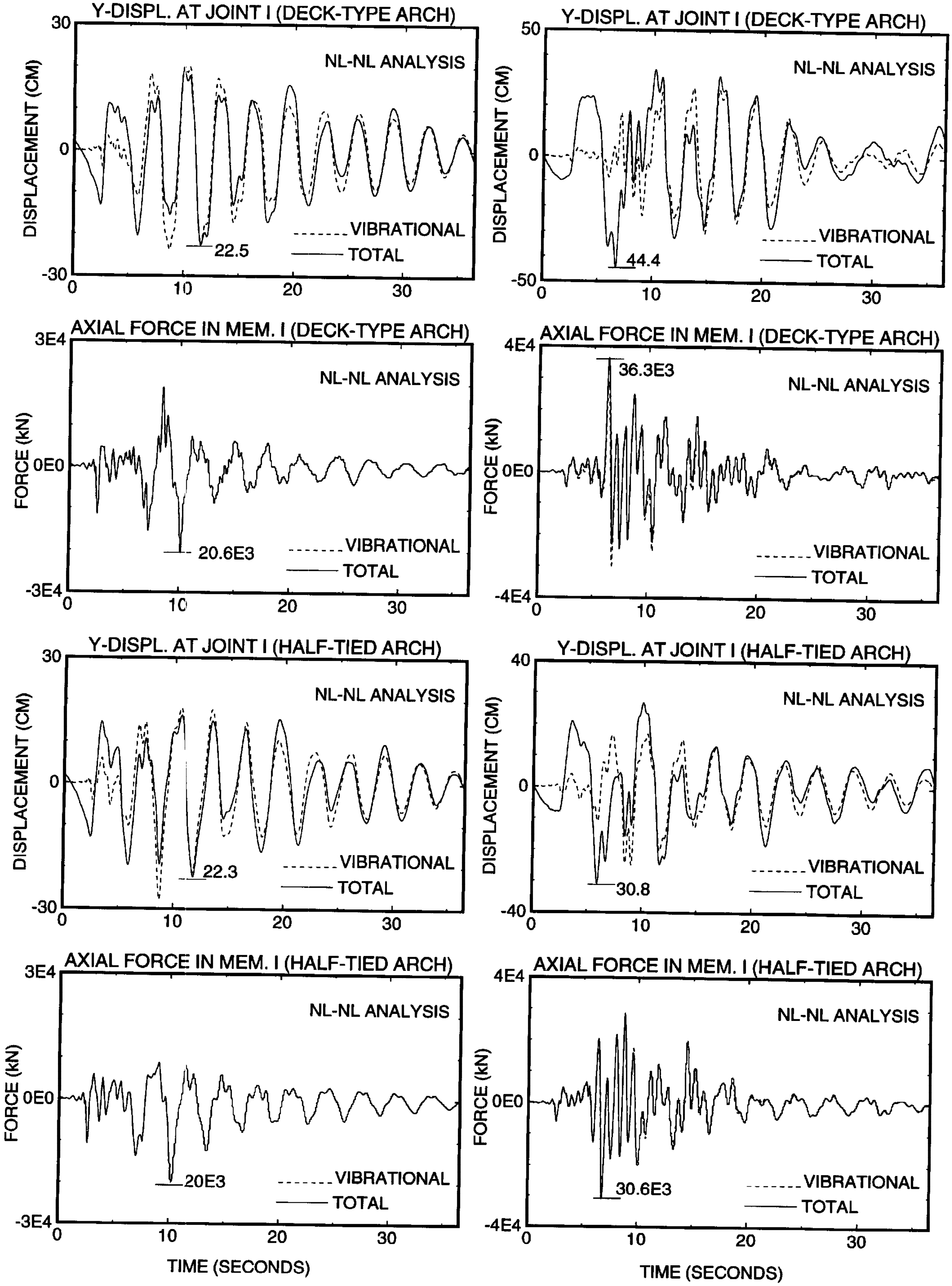

(a) Response to uniform seismic excitation.

(b) Response to multiple-support excitation.

Fig. 4. Comparison between the response to uniform and multiple-support excitations.