EFFECT OF LIGHTWEIGHT CONCRETE ON THE SEISMIC BEHAVIOR OF A BRIDGE WITH TALL BEARINGS

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ABSTRACT

The primary use of structural lightweight concrete is to reduce the dead load of a concrete structure, which allows the designer to reduce the size of columns, footings and other load bearing elements. This paper mainly focuses on modeling the nonlinear behavior of a typical bridge in Georgia rehabilitated with tall bearings subjected to seismic loads. A comparison is made between a bridge model with an existing, normal-weight concrete bridge and one made of a lightweight concrete slab on steel girder bridge to show the effects of a lightweight concrete deck on the structural responses. Since the dead weight of the entire bridge is reduced by a considerable extent due to these mass variations, significant differences can be observed in the seismic behavior, pounding of decks, and interaction between the superstructure-bearing-substructure. SAP 2000 is used as the analysis software to compare these models that are subjected to synthetic and recorded ground motions of varying intensities.

Keywords: Lightweight concrete, tall bearings, nonlinear modeling, seismic analysis

INTRODUCTION

With the increasing demand of consumers, the transportation sector is lobbying for larger, over-height vehicles to transfer commodities throughout the country. However, many bridges throughout the United States have already been damaged due to existing over-height vehicles that have collided into these bridges, resulting in significant direct and indirect costs. To reduce the likelihood of vehicular collisions, the Georgia Department of Transportation (GDOT) has elevated more than 50 bridges in Georgia alone with a special class of tall bearings referred to as steel pedestals to increase the vertical clearance height (Fig. 1). Steel pedestals can be defined as W-shaped, stocky steel columns having 1 inch top and bottom steel plates. They are connected to a girder by anchor bolts, and are attached to the bent cap using either a pair of L-shaped angles welded to the pedestal base plate for which the anchor bolts pass through the holes within the L-shaped angles, or through anchor bolts that pass through holes drilled into the base plate of the pedestal cross-section. The pedestals rest on a 1/8 inch elastomeric bearing pad is placed between bearing and bent cap for improved flexibility and shear capacity[1].

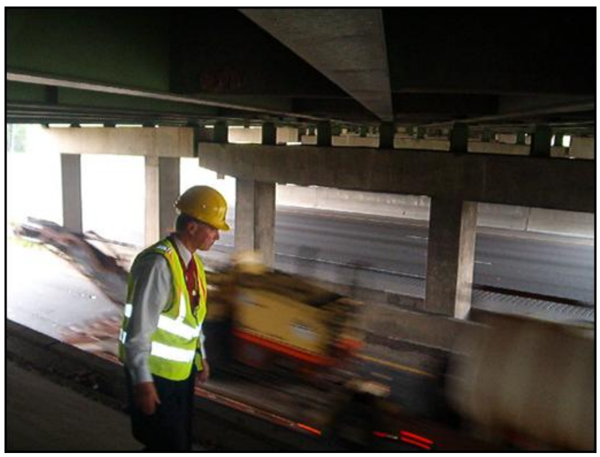


Fig. 1 Bridge in Georgia rehabilitated with steel pedestals to increase vertical clearance

Of these bridges with steel pedestals, many are multi-span simply supported (MSSS) that were constructed more than 50 years ago and may be more vulnerable to seismic demands given the addition of the steel pedestals that transfer vertical loads similar to existing rocker bearings. Rocker bearings range in height of approximately 20.5" (0.52 m) high compared to steel pedestals (tall bearings), which range in height up to 33.5" (0.85 m)[1, 2]. Past research has shown high-type (rocker) bearings to perform unsatisfactorily during earthquakes, where several MSSS bridges with rocker bearings have been damaged in the Guatemala City earthquake in 1976 (Guatemala), Eureka earthquake in 1980 (California, USA), and the Kobe earthquake in 1995 (Japan)[1, 3]. In fact, the research concluded that the failures of those MSSS bridges were mainly due to the lack of strength, ductility and stability of the rocker bearings[1, 3-7]. The seismic effects on older bridges were even more critical, for instance, the damage of rocker bearings in the Loma Prieta earthquake 1989 (California, USA), the keeper plates failure in the Talamanca earthquake 1991(Costa Rica), and toppling of rocker bearings after the Scott Mills earthquake 1993 (Oregon, USA)[1, 8.]

As such, GDOT's main concern was the seismic performance of these steel pedestals, which were shown to be stable and resistant to low seismic loads that may be expected in Georgia.[1] Given the experimental test data available in the form of force-displacement hysteretic curves for the steel pedestals, this analytical study aims to investigate the relationship between mass of the superstructure and corresponding seismic behavior of tall bearings (steel pedestals). The force-displacement hysteretic behavior of these pedestals is incorporated into a detailed analytical model developed in SAP 2000 and evaluated using nonlinear time history analysis. Therefore, the primary objectives of this study are: 1) to characterize the structural behavior of a candidate bridge in Georgia rehabilitated with steel pedestals in a three-dimensional analytical model developed using SAP 2000; 2) to study the effects of varying mass of the structure (lightweight concrete slab on a concrete girder bridge); and 3) to analyze the effects of synthetic and recorded ground motions of varying intensities on the displacements of deck, abutments, column, bearings and the force exerted at the bearing-bent cap connection joint.

ANALYTICAL MODELING USING SAP 2000

SAP 2000 is a finite element commercial software package that provides user friendly features like a graphic user interface and bridge modeler that incorporates structural mechanics and behavior to accurately model a bridge. There are several assumptions made while modeling a particular bridge. These include the boundary conditions, material properties, extent of complexity of the model such as modeling of deck as equivalent beam type or shell type, modeling of column supports, and modeling of soil–abutment interaction, deck gap elements, and consideration of skew effects.

The research is based on seismic design guidelines taken from several references[9-11]. Though these guidelines are mainly used in the actual bridge industry and not necessarily for research purposes, nevertheless, they provided enough information for modeling key parameters of a bridge, and the important recommendations that have been considered in our research. This research is based on the nonlinear time history analysis of the bridge. Nonlinear behavior is considered for modeling of bearings, deck gap elements, and columns, while the composite deck and bent cap are modeled as linear elastic elements. The column has been modeled as a confined concrete model. The reason for choosing a nonlinear model is that in case a linear model is used for the seismic analysis, it will indicate that some components of the bridge are overstressed, even if they are actually not. After certain stress limits when a material approaches the nonlinear regime, there is an internal redistribution of forces that leads to several changes in the properties of that member like its effective stiffness and energy dissipation characteristics. Hence, there is a significant deviation in the nonlinear seismic response and the corresponding elastic response [15, 11]. Also, six degrees of freedom at each node are used for analysis of the entire structure.

PHYSICAL DESCRIPTION OF CANDIDATE BRIDGE

The analysis model of the bridge developed in this study is the geometrical replica of a bridge located in Liberty County, Georgia. It is a concrete slab on steel girder bridge that was elevated with steel pedestal bearings to increase the vertical clearance height of the bridge to 17' (5.2 m). The total length of the bridge is 407' (124 m), having six spans with 39.37' (12 m) long end spans, and middle spans of 72.18' (22 m) and 91.86' (28 m) long respectively. There are even numbers of spans, and the bridge is symmetric. The height of the columns supporting the superstructure is 22.96' (7 m), and each bent is having three columns. The bent and abutment are skewed at angle of 18.25°, with the longitudinal axis. The total width of the deck is 32.81' (10 m). The deck gap elements are located at end of each end span on either direction. To determine the variation in the analysis, the deck was replaced by a lightweight concrete slab on steel girder bridge, which considerably reduces the mass and thereby affects the overall behavior of the bridge.

MODEL GEOMETRY AND FINITE ELEMENT TYPES

A three-dimensional model having frame elements, commonly referred to as lumped mass stick models, is used for the seismic analysis of this bridge. This is a typical model used in industry and research. For any seismic analysis it is a requirement that the model configuration should accurately represent the actual mass, stiffness and damping of the structure to achieve desired results.

In this model, the mass of the whole structure is defined as accurately as possible. The bridge modeler feature of SAP 2000 allows defining the various geometric features of every component of the bridge including deck, column, abutment, bent, and it also allows the user to define the material properties accordingly based on the section properties, and dimension of the component, and material. Based on these parameters, the model accurately calculates the mass of each component, and thus the whole bridge. In this analysis the dead load is implicitly included, but the live load has been excluded as it is not significant [9, 12].

The distribution of mass depends on number of finite elements used to model any component of the bridge. In general a minimum of three elements per column, four elements per deck span and one element for bent cap should be considered in a linear elastic model. Also, the number of modes of vibration to be considered should capture 90% of total mass in both longitudinal and transverse direction.

The stiffness of any bridge component in nonlinear range should also be accurately modeled. Large joints can be represented as rigid links, or end offsets with a definite rigidity factor. The effects of cracking, tension rupture etc should also be considered in finding effective stiffness. In this model, the cracked section moment of inertia of column is used by reducing the original by a factor of 0.7 [11, 12].

Model development and assumptions

The three dimensional model of the candidate bridge located in Liberty County, GA is shown in Fig 2. The subsequent sections describe the modeling of each component and the assumptions made.

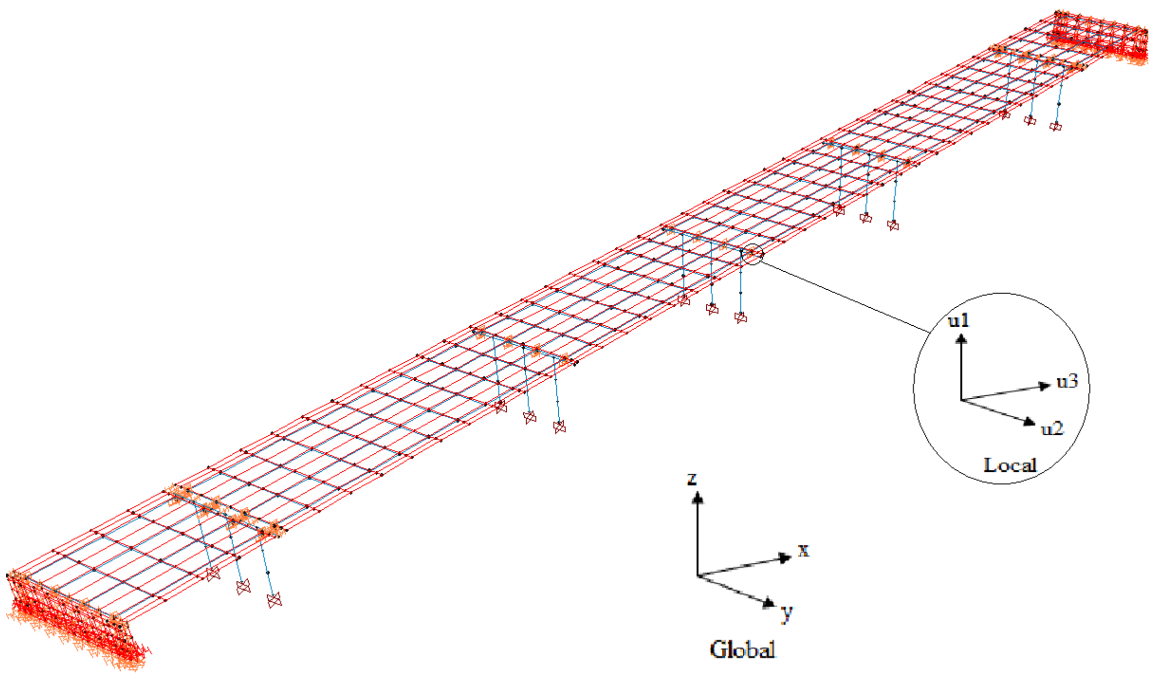


Fig. 2 Three-dimensional view of the candidate bridge used in the analysis

The important geometric features of the bridge can be summarized in Table 1.

Table 1: Geometric details of the bridge		
1)	Total length	124 m (406 ft)
2)	Span 1,6	12 m (39 ft)
3)	Span 2,5	28 m (92 ft)
4)	Span 3,4	22 m (72 ft)
5)	Height of column	7 m (23 ft)
2)	Skew	18.25°
3)	Number of column per bent	3
4)	Position of deck gap element	at 12 m (39 ft), 112 m (367 ft)from starting station

Deck

The slab of the deck is modeled as a shell element and the girders are modeled as beam elements. It is basically modeled as linear elastic member and there is no non-linearity associated with it. The bridge modeler has the option of defining the deck section based on the various templates. After choosing the desired template, the data was modified according to the details of the candidate bridge. The number of finite elements in which the deck has been divided depends on the span length. For this study, a compressive strength for the reinforced concrete is defined as 4 ksi for one model and 6 ksi for the lightweight concrete model. The deck properties are specified in Table 2. The nonlinear deck gap element is modeled as a series connection of equivalent stiffness with an initial gap in the longitudinal direction only. The stiffness of deck gap element is assumed to be 12.56 kip/in (2200 kN/m) and the initial gap as 1'' (25 mm). The deck gap element should not be too stiff that surrounding objects and should be a compression only member. The modeling of the foundation elements, i.e. pile caps and piles, has been excluded from the scope of the current investigation.

Table 2 Properties of deck		
a) Cross-sectional properties of lightweight concrete slab 7'' on steel girder deck (LCS)		
1)	Area of cross section	3.82 m^2 (41.12 ft^2)
2)	Width	10 m (32.8 ft)
3)	Material (light weight concrete)	41.38 MPa (6 ksi)
4)	Moment of Inertia	0.97 m^4 (112.38 ft^4)
b) Cross-sectional properties of 8'' concrete slab on steel girder deck (NCS)		
1)	Area of cross section	4.12 m^2 (44.33 ft^2)
2)	Width	10 m (32.8 ft)
3)	Material (concrete)	27.60 MPa (4 ksi)
4)	Moment of inertia	1.04 m^4 (120.41 ft^4)
c) Cross-sectional properties of concrete slab on concrete girder deck (NCDG)		
1)	Area of cross section	6.32 m^2 (68.00 ft^2)
2)	Width	10 m (32.8 ft)
3)	Material (concrete)	27.60 MPa (4 ksi)
4)	Moment of Inertia	2.54 m^4 (240.82 ft^4)

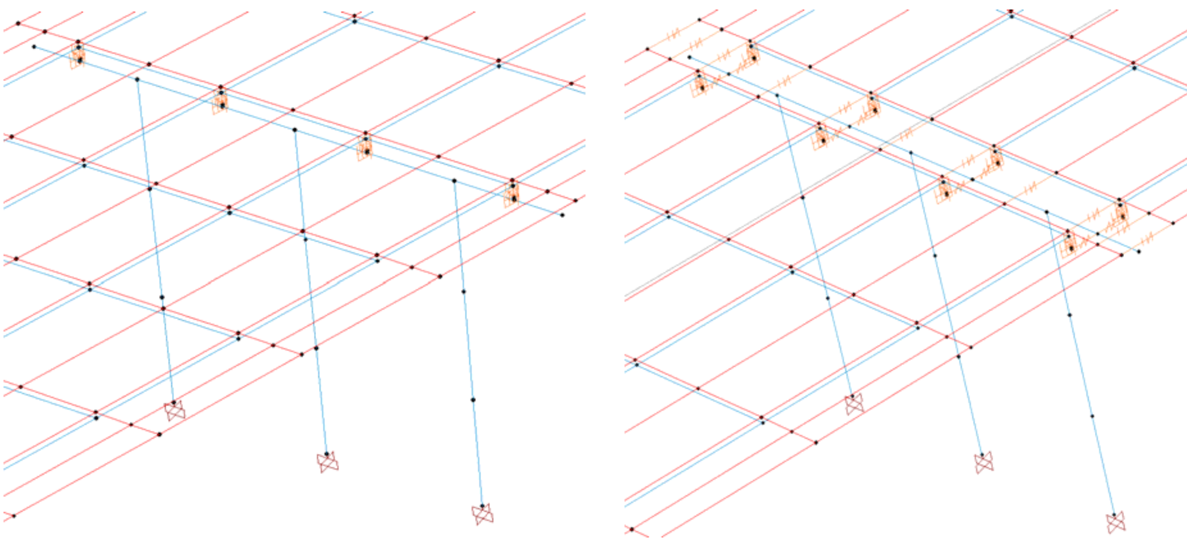
Columns

The column has been modeled as a non linear element, having confined concrete model [14]. The concrete used is having a compressive strength of 4 ksi (27.60 MPa). The column is having height of 22.96' (7 m), and is modeled with fixed supports. These supports restrain the movement in all six degrees of freedom. The number of finite elements used to model a column is three. It is having rigid connection with the bent cap. The properties for the columns are specified in Table 3.

Table 3 Cross-sectional properties of column		
1)	Area of cross section (square)	0.83 m^2 (8.93 ft^2)
2)	Material (concrete)	27.60 MPa (4 ksi)
3)	Moment of Inertia	0.057 m^4(6.60 ft^4)

<u>Bent caps</u>

The bent caps are also modeled as linear elastic elements. Though only one element is enough for modeling of the bent cap but due to number of connections, it is divided into a number of elements. It is connected with columns and bearings, and is having rigid connection. Where a deck gap is present, it may have a rigid offset too, connecting to the bearing. Both these modifications are shown in the Fig. 3. The bent is skewed at angle of 18.25°, with the longitudinal axis of the bridge. The properties for the bent caps are specified in Table 4.



a) b)

Fig. 3 Model of bent a) without deck gap element b) with deck gap element

Table 4 : Cross section properties of bent		
1)	Area of cross section (square)	0.83 m^2 (8.93 ft^2)
2)	Material (concrete)	27.60 MPa (4 ksi)
3)	Moment of inertia	0.057 m^4 (6.60 ft^4)

<u>Bearings</u>

The bearings are also modeled as nonlinear link elements having multi-step plastic force deformation and moment curvature relation, which can be easily defined in the section properties of a link element in SAP 2000. The effective stiffness properties are also given which are used in SAP to calculate the vibration modes. The expansion bearings are having translational springs in the bottom allowing them to slide at base. The force-deformation plots are based on experimental tests [1] and are shown in Fig. 4.

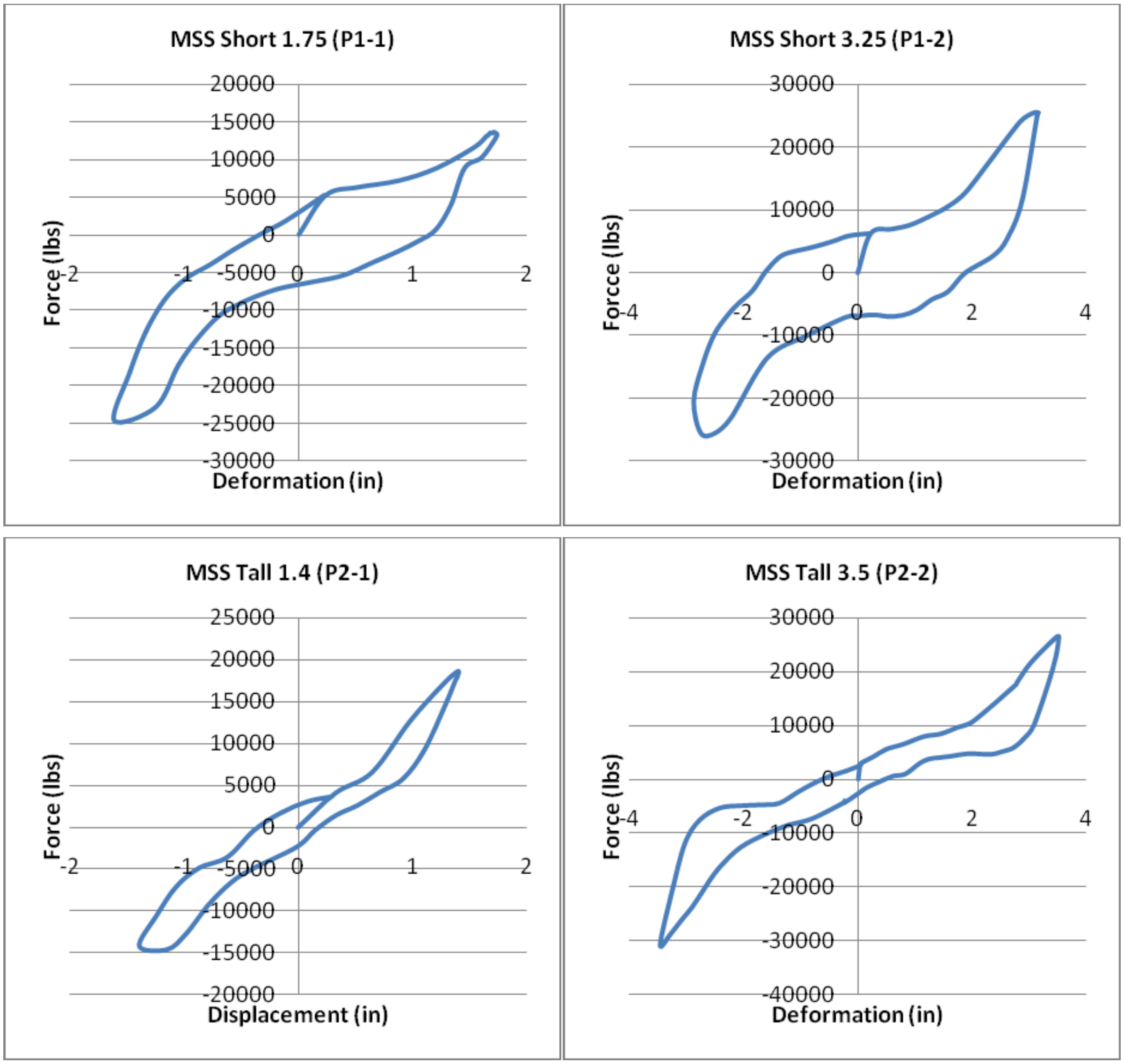


Fig. 4 Force-deformation hysteretic behavior of one steel pedestal[1]

Abutments

The abutment includes a backwall modeled using shell elements attached with the deck by means of the bearing. The wingwall is not included, and the abutment is attached with soil springs. The model view of the abutment is shown in Fig. 5. The backwall properties are taken from the construction drawings. The soil stiffness properties are taken from default values available in SAP 2000 software, which are 1.261E+10 kN/m in the x, y, and z directions (linear stiffness) and 3.514E+09 kN/m in r_x, r_y, and r_z directions (rotational stiffness).

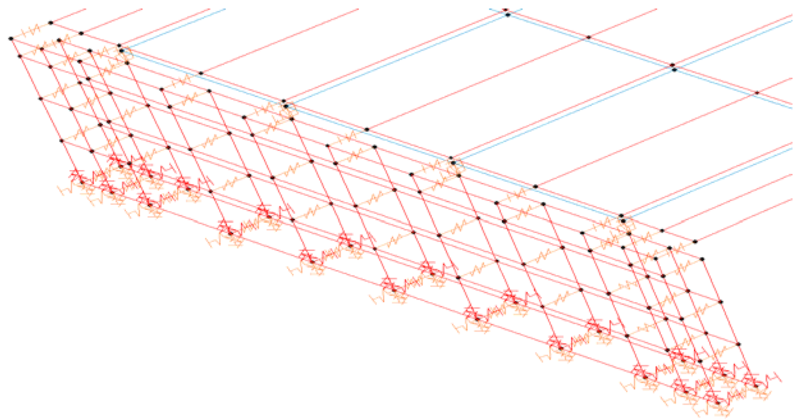


Fig 5 Model of abutment

GROUND MOTION DATA USED

This study is using these eight ground motions. These motions represent low-to-moderate-to-high intensity earthquakes at various recurrence intervals. Two motions are synthetically developed based on the site-specific conditions for Liberty County, Georgia for a 2% and 10% probability of exceedance[15] and the other two are recorded motions from earthquakes in the state of California[13]. The time history plots of these ground motions are shown in Fig. 3.

1) Liberty County 475 , GA (PGA=0.04 g)
2) Liberty County 2475, GA (PGA=0.2 g)
3) Imperial Valley (El Centro), CA (PGA=0.35g)
4) Northridge , CA (PGA=0.8g)

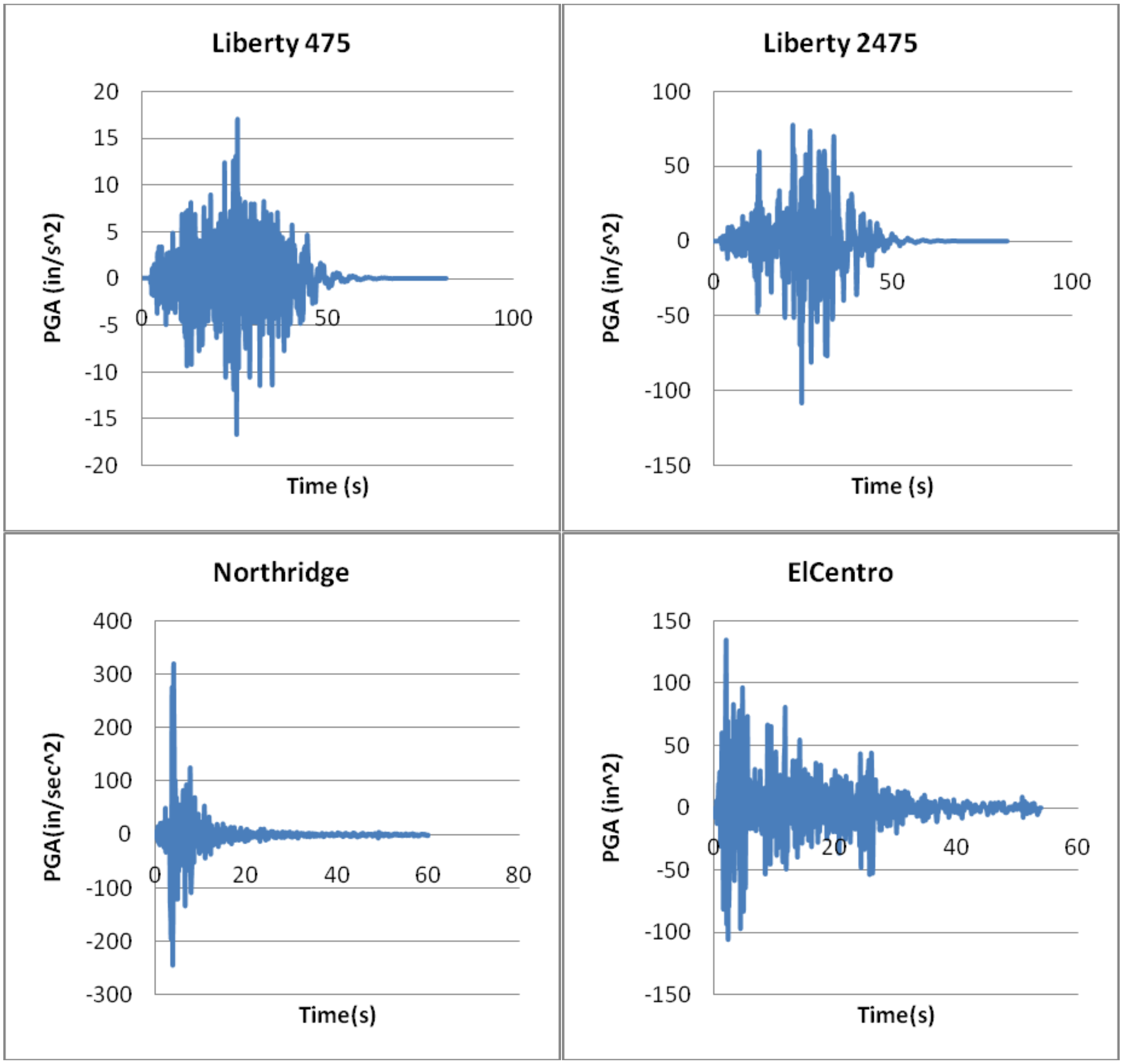


Fig 6: Plots of time histories used for nonlinear time history analysis

ANALYSIS OF RESULTS

The bridge model is subjected to synthetic ground motions and the nonlinear time history analysis is carried out in SAP 2000. The results of the analysis are summarized in Tables 5-8.

MODAL TIME HISTORY OUTPUT

Table 5 gives modal output of each model. As mentioned before Ritz Modal Analysis was used to find out the modal behavior as it is preferred for the non linear time history functions. Though hundred modes were sought, the results of the first four modes are provided. As expected, when the mass of the structure increased, so does its structural period. Having a lightweight concrete deck on a steel girder reduces its fundamental mode of frequency by almost half when compared to the fundamental mode of the normal-weight concrete bridge with concrete girders for this study. Depending on the seismic demand, this can prove to be beneficial such that the fundamental mode does not occur near the fundamental mode of the ground motion. In the case of the bridge modeled with the tall bearings using the experimental data from P2-1 and P2-2 steel pedestal tests, the periods were slightly higher if not the same for Mode 1 given the decrease in initial stiffness of the taller bearings.

Table 5 Modal Frequency Output

Mode	Time Period (s)					
	LCS P1-1 & P1-2	LCS P2-1 & P2-2	NCS P1-1 & P1-2	NCS P2-1 & P2-2	NCDG P1-1 & P1-2	NCDG P2-1 & P2-2
1	0.77	0.77	0.91	0.93	1.55	1.55
2	0.68	0.65	0.82	0.78	1.37	1.31
3	0.37	0.36	0.44	0.43	0.81	0.76
4	0.35	0.35	0.42	0.42	0.71	0.70

DISPLACEMENT OUTPUT

The displacement of the deck/top node of the bearing, and top node of the column generally shows an increasing trend when the mass of the superstructure is increased. Though, when the tall bearings are used these displacements are less. In either case the displacements are not alone sufficient to cause unseating and they are not exceeding service state limits. Table 6 shows the displacement of the deck/top node of the bearing, bottom node of the bearing to indicate sliding at the pedestal base, and top node of the column.

Table 6 Joint Displacement Output

Ground motion & Model Type	Units	Deck / Bearing Top (mm / in)		Bearing Bottom (Translational Spring) (mm / in)		Column (mm/ in)	
		Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
	Bearing Type : P1-1 & P1-2						
1) Liberty 475							
LCS	SI	10.43	8.79	2.87	-2.00	-2.40	-1.38
	US	0.41	0.35	0.11	-0.08	-0.09	-0.05
NCS	SI	12.21	-14.15	-2.91	-3.00	-2.52	-1.84
	US	0.48	-0.56	-0.11	-0.12	-0.10	-0.07

NCDG	SI	10.96	-14.09	3.05	-3.02	2.51	-2.04
	US	0.43	-0.55	0.12	-0.12	0.10	-0.08
2) Liberty 2475							
LCS	SI	-87.85	53.84	-23.25	-12.52	-18.30	-9.16
	US	-3.45	2.12	-0.91	-0.49	-0.72	-0.36
NCS	SI	-99.24	54.11	-26.68	12.80	-20.58	-8.68
	US	-3.90	2.13	-1.05	0.50	-0.81	-0.34
NCDG	SI	-178.22	113.46	-44.50	26.17	-33.04	16.61
	US	-7.00	4.46	-1.75	1.03	-1.30	0.65
3) El Centro							
LCS	SI	-8.98	6.03	-23.34	14.20	-18.00	20.80
	US	-0.35	0.24	-0.92	0.56	-0.71	0.82
NCS	SI	-8.43	7.90	22.72	19.66	-17.84	13.04
	US	-0.33	0.31	0.89	0.77	-0.70	0.51
NCDG	SI	-110.29	89.25	-25.98	21.73	21.26	14.70
	US	-4.33	3.51	-1.02	0.85	0.84	0.58
4) Northridge							
LCS	SI	-209.05	127.93	-53.93	31.41	-41.37	20.80
	US	-8.22	5.03	-2.12	1.23	-1.63	0.82
NCS	SI	-249.24	161.46	-70.03	39.00	-56.20	25.73
	US	-9.80	6.35	-2.75	1.53	-2.21	1.01
NCDG	SI	-501.02	277.09	-126.30	64.11	-93.63	43.91
	US	-19.69	10.89	-4.96	2.52	-3.68	1.73
	Bearing Type : P2-1 & P2-2						
1) Liberty 475							
LCS	SI	3.82	4.48	1.69	-1.95	1.65	-1.18
	US	0.15	0.18	0.07	-0.08	0.06	-0.05
NCS	SI	4.76	-8.56	1.71	-2.12	1.65	-1.29
	US	0.19	-0.34	0.07	-0.08	0.06	-0.05
NCDG	SI	6.53	-11.21	1.83	-2.19	1.74	-1.79
	US	0.26	-0.44	0.07	-0.09	0.07	-0.07
2) Liberty 2475							
LCS	SI	-47.23	-40.51	-9.74	-10.99	-9.5	-7.17
	US	-1.86	-1.59	-0.38	-0.43	-0.37	-0.28
NCS	SI	-57.97	-48.41	-12.50	-13.22	-11.96	-8.69
	US	-2.28	-1.90	-0.49	-0.52	-0.47	-0.34
NCDG	SI	102.77	57.23	-26.70	-21.88	-25.64	-14.68
	US	4.04	2.25	-1.05	-0.86	-1.01	-0.58
3) El Centro							
LCS	SI	45.60	-51.88	-9.51	-13.53	-9.51	-8.56
	US	1.79	-2.04	-0.37	-0.53	-0.37	-0.34
NCS	SI	44.59	-51.12	-9.80	-12.26	-9.55	-7.78
	US	1.75	-2.01	-0.39	-0.48	-0.38	-0.31
NCDG	SI	81.34	-61.63	16.70	-15.40	15.82	-9.78
	US	3.20	-2.42	0.66	-0.61	0.62	-0.38
4) Northridge							
LCS	SI	-157.94	-109.68	-43.48	-31.20	-41.96	-22.32
	US	-6.21	-4.31	-1.71	-1.23	-1.65	-0.88
NCS	SI	175.84	-149.82	45.37	-42.54	43.69	-28.75
	US	6.91	-5.89	1.78	-1.67	1.72	-1.13
NCDG	SI	-339.48	-270.88	-80.77	-70.79	-76.89	-45.32
	US	-13.34	-10.65	-3.17	-2.78	-3.02	-1.78

POUNDING BEHAVIOR

The effect of pounding is not occurring in the low intensity earthquake, i.e., Liberty 475, but does occur at the abutments or at the joints for the moderate-to-high seismic loads, i.e. Liberty 2475, El Centro and Northridge ground motions. Pounding can be a critical factor for failure of adjacent bridge components for these earthquakes. Pounding is more pronounced as expected when the mass of the superstructure is increased since the structural period has increased, thereby making the structure more flexible. Table 7 shows the deformation of the deck gap element, which represents the effects of pounding when the gap of 1" (25mm) is exceeded. The force transferred to the adjacent superstructure in the case of pounding is also recorded and noted. For high intensity earthquakes, the force is enough to cause spalling of the concrete and damage can be extensive in some cases.

Table 7 Pounding (maximum deck gap deformation [Δ] and force during impact)

Ground motion & Model Type	Model Type	Abutment (mm/ in)	Deck joint (mm/ in)	Pounding ($\Delta > 25$ mm Or $\Delta > 1$ in) (Y/N)	Axial (kN / Kips) (at abutment)	Axial (kN / Kips) (at joint)
	Bearing Type : P1-1 & P1-2					
1) Liberty 475						
LCS	SI	3.11	10.50	N	--	--
	US	0.12	0.41		--	--
NCS	SI	4.24	12.42	N	--	--
	US	0.17	0.49		--	--
NCDG	SI	10.50	12.81	N	--	--
	US	0.41	0.50		--	--
2) Liberty 2475						
LCS	SI	25.82	75.39	Y	0.084	8.23
	US	1.01	2.96		0.02	1.84
NCS	SI	40.54	81.37	Y	3.029	9.46
	US	1.59	3.20		0.68	2.12
NCDG	SI	74.81	151.72	Y	9.88	24.00
	US	2.94	5.96		2.21	5.38
3) El Centro						
LCS	SI	24.59	86.44	Y (at joint)	--	12.21
	US	0.97	3.40		--	2.74
NCS	SI	44.83	102.36	Y	3.89	9.82
	US	1.76	4.02		0.87	2.20
NCDG	SI	68.00	105.51	Y	8.52	16.02
	US	2.67	4.15		1.91	3.59
4) Northridge						
LCS	SI	104.41	188.50	Y	15.80	32.62
	US	4.10	7.41		3.54	7.31
NCS	SI	150.10	176.83	Y	24.94	30.28
	US	5.90	6.95		5.59	6.78
NCDG	SI	179.71	326.11	Y	30.86	60.14
	US	7.06	12.82		6.91	13.47

	Bearing Type : P2-1 & P2-2					
1) Liberty 475						
LCS	SI	1.71	2.22	N	--	--
	US	0.07	0.09		--	--
NCS	SI	2.27	3.04	N	--	--
	US	0.09	0.12		--	--
NCDG	SI	3.18	5.60	N	--	--
	US	0.12	0.22		--	--
2) Liberty 2475						
LCS	SI	10.14	38.36	Y (at joint)	--	2.59
	US	0.40	1.51		--	0.58
NCS	SI	15.66	49.28	Y (at joint)	--	4.77
	US	0.62	1.94		--	1.07
NCDG	SI	48.34	70.75	Y	4.59	5.94
	US	1.90	2.78		1.03	1.33
3) El Centro						
LCS	SI	20.71	37.39	Y (at joint)	--	5.65
	US	0.81	1.47		--	1.27
NCS	SI	20.96	39.32	Y (at joint)	--	1.58
	US	0.82	1.55		--	0.35
NCDG	SI	37.20	60.39	Y (at joint)	--	2.84
	US	1.46	2.37			0.64
4) Northridge						
LCS	SI	38.46	101.97	Y	8.89	15.31
	US	1.51	4.01		1.99	3.43
NCS	SI	56.71	122.05	Y	8.63	15.14
	US	2.23	4.80		1.93	3.39
NCDG	SI	143.53	226.91	Y	17.95	40.30
	US	5.64	8.92		4.02	9.03

FORCE OUTPUT

Table 8 shows the force transmitted to the bearing, its base connection, and the column. In high intensity earthquakes like Northridge, the column is showing yielding at the base. Similar behavior can also be observed in the case of bearings for such high intensity earthquakes. The A490 anchor bolts are used to connect the bearing to the bent cap having diameter of 1.25 in (31.75 mm). From the analysis results the connecting bolts are safe in tension and shear in the case of low or moderate level of earthquake. But it fails in shear in case of high intensity earthquakes like Northridge, which can bring about the unseating of the bearings.

Table 8 Maximum forces transmitted to bridge components

		Bearing (kN / Kips)		Bearing Base Connection (kN / Kips)		Column (kN/ Kips)	
	Bearing Type : P1-1 & P1-2						
Ground motion	Model Type	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)
1) Liberty 475							
LCS	SI	14.79	20.62	-22.32	-19.79	29.44	-30.06
	US	3.31	4.62	-5.00	-4.43	6.59	-6.73
NCS	SI	20.19	21.98	-30.04	-23.25	30.21	-43.74
	US	4.52	4.92	-6.73	-5.21	6.77	-9.80
NCDG	SI	23.35	25.69	-30.25	-21.84	27.87	-46.22
	US	5.23	5.75	-6.78	-4.89	6.24	-10.35
2) Liberty 2475							
LCS	SI	56.27	91.39	-72.98	-112.08	188.40	126.47
	US	12.60	20.47	-16.35	-25.11	42.20	28.33
NCS	SI	60.02	107.35	-94.14	-114.99	200.18	180.29
	US	13.44	24.05	-21.09	-25.76	44.84	40.38
NCDG	SI	-210.87	-139.60	-120.37	-132.16	303.01	270.07
	US	-47.23	-31.27	-26.96	-29.60	67.87	60.50
3) El Centro							
LCS	SI	-73.72	98.28	-104.32	-114.64	189.35	220.27
	US	-16.51	22.01	-23.37	-25.68	42.41	49.34
NCS	SI	81.63	-100.08	-109.02	-116.44	-195.64	214.45
	US	18.29	-22.42	-24.42	-26.08	-43.82	48.04
NCDG	SI	-97.59	113.46	-113.44	-113.45	-221.46	262.95
	US	-21.86	25.42	-25.41	-25.41	-49.61	58.90
4) Northridge							
LCS	SI	-205.972	-130.156	-119.60	-127.73	370.30	442.18
	US	-46.14	-29.15	-26.79	-28.61	82.95	99.05
NCS	SI	-270.44	-162.86	-124.45	-143.96	516.03	597.80
	US	-60.58	-36.48	-27.88	-32.25	115.59	133.91
NCDG	SI	-581.97	-222.40	-143.08	-170.95	818.00	890.53
	US	-130.36	-49.82	-32.05	-38.29	183.23	199.48
	Bearing Type : P2-1 & P2-2						
1) Liberty 475							
LCS	SI	-17.10	-13.17	-11.65	9.20	-20.19	-32.10
	US	-3.83	-2.95	-2.61	2.06	-4.52	-7.19
NCS	SI	-17.69	-14.18	-11.49	15.65	-20.07	-30.42
	US	-3.96	-3.18	-2.57	3.51	-4.50	-6.81
NCDG	SI	-20.13	-16.89	-11.39	21.65	-18.06	-38.90
	US	-4.51	-3.78	-2.55	4.85	-4.05	-8.71
2) Liberty 2475							
LCS	SI	-64.71	38.11	91.36	-63.38	112.20	-134.29
	US	-14.50	8.54	20.46	-14.20	25.13	-30.08
NCS	SI	-76.19	44.64	143.99	-77.32	125.79	-151.52
	US	-17.07	10.00	32.25	-17.32	28.18	-33.94
NCDG	SI	-124.59	-117.93	314.77	-164.13	255.92	-207.622
	US	-27.91	-26.42	70.51	-36.77	57.33	-46.51

3) El Centro							
LCS	SI	-81.75	-41.81	146.92	-78.76	117.05	-179.23
	US	-18.31	-9.37	32.91	-17.64	26.22	-40.15
NCS	SI	-84.93	-41.49	174.14	-77.83	105.17	-159.43
	US	-19.02	-9.29	39.01	-17.43	23.56	-35.71
NCDG	SI	-98.84	-80.72	288.76	-135.40	-145.32	-167.61
	US	-22.14	-18.08	64.68	-30.33	-32.55	-37.54
4) Northridge							
LCS	SI	-159.85	-163.72	396.82	-212.10	461.15	-345.30
	US	-35.81	-36.67	88.89	-47.51	103.30	-77.35
NCS	SI	-215.00	-220.21	693.30	-274.76	-452.18	-473.42
	US	-48.16	-49.33	155.30	-61.55	-101.29	-106.05
NCDG	SI	-401.69	-351.60	1567.63	-414.50	743.84	-672.68
	US	-89.98	-78.76	351.15	-92.85	166.62	-150.68

The plots for the hysteresis behavior of the bearings for the LCS bridge model having tall bearings with experimental test data from P2-1 and P2-2, and subjected to the Liberty 2475 ground motion are shown below in Fig. 7.

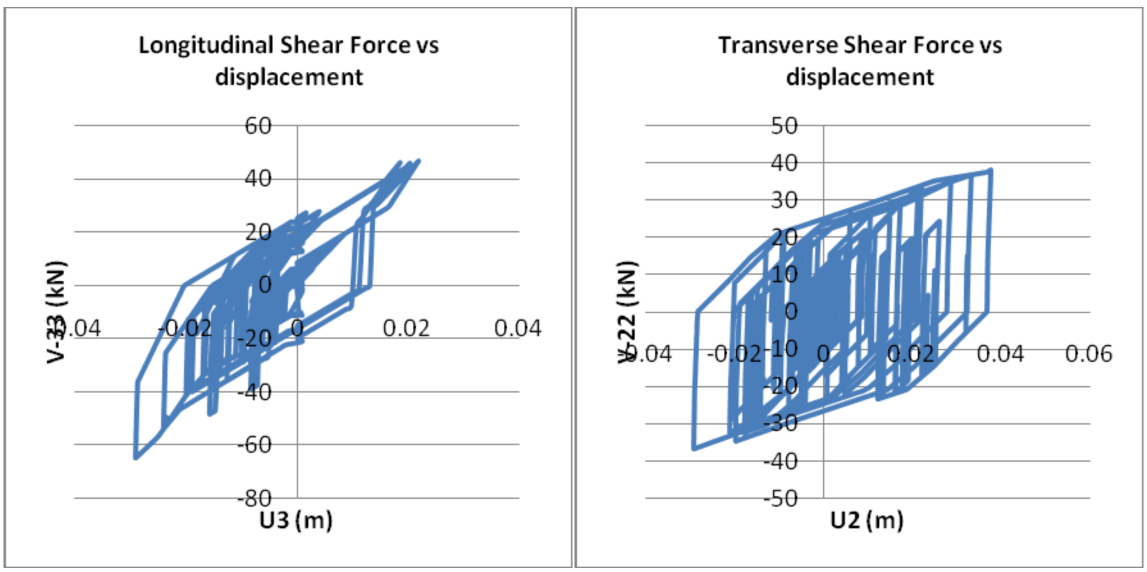


Fig. 7 Shear force-deformation hysteretic output of a steel pedestal

CONCLUSIONS

This study compared three different types of models: one having lightweight concrete slab on a steel girder deck, one having a normal-weight concrete deck on a steel girder bridge, and the other consisting of a normal-weight concrete slab and girder. Due to the reduction in the mass of the bridge the seismic behavior is significantly affected, changing the time period of the structure and the displacement, effects of pounding and risk of possible connection failure is also reduced significantly. Also, it can be deduced from the results that the tall bearings can lead to significant shear forces in the connection bolts, which transfer larger forces into the columns, especially in the event of high intensity earthquakes. This can cause shear failure in the anchor bolts, thereby causing unseating of the bearings. Nevertheless, the performance of such tall bearings is acceptable for regions of low-to-moderate level earthquakes, and is to be suitable for combinations of models having lightweight concrete and varying girders consisting of both concrete and steel. The results also showed that the effect of pounding does not occur in the event of the low intensity earthquake, i.e., Liberty 475, but does occur at abutments or at the joints for the moderate-to-high seismic loads, i.e. Liberty 2475, El Centro and Northridge earthquakes. Pounding can be a critical factor for failure of adjacent bridge components for these earthquakes. Moreover, pounding is more pronounced as expected when the mass of the superstructure is increased since the structural period has increased, thereby making the structure more flexible. Overall, the tall bearings performed satisfactorily and revealed some interesting phenomena related to the effects of pounding and potential unseating of the bridge decks given an implied failure of the anchor bolts based on the shear forces in the bridge components as shown by the SAP 2000 analyses.

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