ASSESSMENT OF CRITICAL PARAMETERS THAT AFFECT THE SEISMIC PERFORMANCE OF BRIDGE STEEL PEDESTALS

A Thesis

by

SIDDHARTH SRIVASTAVA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Monique H. Head
Committee Members,	Jose Roesset
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ABSTRACT

Assessment of Critical Parameters That Affect the Seismic Performance

of Bridge Steel Pedestals. (December 2008)

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Chair of Advisory Committee: Dr. Monique H. Head

The Georgia Department of Transportation has been installing steel pedestals on bridges, ranging in height up to 33½" (0.85m) to increase the vertical clearance of many multi-span simply-supported and multi-span continuous bridges in Georgia. But there is a concern about the performance of these steel pedestals as they are designed without seismic consideration and may perform poorly compared to high-type steel "rocker" bearings, which were found to be unstable supports in previous earthquakes.

This research models a candidate bridge using experimental data that captures the force-displacement hysteretic behavior of the steel pedestals. The results show how these steel pedestals behave when subjected to a range of ground motions. Nonlinear time history analysis is conducted using SAP 2000 software on a three-dimensional model of the candidate bridge. In addition, parametric studies of various critical parameters that can affect the seismic performance of the bridge are investigated, such as 1) varying the mass of the structure, 2) varying the stiffness of the deck joint, 3) varying column heights, and 4) seismic retrofitting using cable restrainers.

The results show that these pedestals should not be used in regions of high seismicity, and in regions of low seismicity, it is likely that they need to be retrofitted.

They can, although, be used safely in regions of low seismicity. In addition, it was shown that the mass of a superstructure and height of the columns significantly affect the behavior of these steel pedestals, and should be given a careful consideration before usage. It was also shown that the stiffness of the expansion joints does not significantly affect the displacement of the steel pedestals and the forces transmitted to them. However, if the expansion joints are too stiff compared to the adjacent bridge components, then the forces transferred during pounding of superstructure is increased significantly.

DEDICATED TO MY PARENTS

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. Monique H. Head, for all her encouragement and guidance throughout the entire duration of my graduate studies. I am indeed fortunate to get an opportunity to work under her supervision. I would also like to thank my other thesis committee members, Dr. Roesset and Dr. Muliana, for their kind help and constant feedback.

I am extremely grateful to my parents and my sister for their constant emotional and moral support. My parents will always remain my source of inspiration. Throughout my life, they have been my pillars of strength and without them I would not have succeeded in achieving my goals. Last, but not the least, I would like to thank all my friends and the faculty members of NIT Durgapur for all their help and support.

LIST OF ABBREVIATIONS AND SYMBOLS

P1-1 and others	Pedestal configurations with loading direction and connection details
NCS	Normal-weight concrete slab on steel girder bridge model
LCS	Lightweight concrete slab on steel girder bridge model
NCDG	Normal-weight concrete slab and girder bridge model
NCS-DG	NCS bridge model with higher stiffness of expansion joint
NCS-C	NCS bridge model with variation of column height along the length of the bridge
NCS-R	NCS bridge model retrofitted by using cable restrainers
NCS P1-1, 1-2 and others	NCS bridge model having P1-1, 1-2 pedestal configuration
BTJ	Top joint of the bearing or pedestal
TTJ	Top joint of the translational spring or bottom joint of pedestal
B	Bearing or pedestal
BTJ-1 and others	Top joint of the bearing seated upon Bent 1 (Abutment)
BTJ-2a	Top joint of the bearing seated upon Bent 2 and located before the expansion joint
BTJ-2b and others	Top joint of the bearing seated upon Bent 2 and located after the expansion joint
‘C/D’ ratio	Capacity to demand ratio of any parameter
Bent ‘a’	The bent cap having no expansion joint and more seat width of 450 mm

Bent 'b'	The bent cap having expansion joint and less seat width of 300 mm
X	Longitudinal direction (Global axis)
Y	Transverse direction (Global axis)
Shear x-x	Shear force along longitudinal direction
Shear y-y	Shear force along transverse direction
W	Seat Width

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1. INTRODUCTION

1.1. PROJECT DESCRIPTION

With the increasing demand from consumers and the need to transport massive goods throughout the country, the transportation sector is relying upon larger vehicles to transfer these commodities. However, this demand can sometimes prove to be hazardous if those over-height vehicles exceed the vertical clearance provided and thus collide into the bridge superstructure causing damage upon impact. Such an impact can lead to massive economical losses in the form of redesigning and rebuilding the bridge requiring expertise from engineers, contractors and manpower to complete the job. Indirect losses due to halting and rerouting the traffic can lead to wastage of fuel and time of the commuters. For instance, in one of the accidents, an oil tanker collided with the I-44 bridge in Lebanon, Missouri resulting in a total loss of $ 4.5 million. It took 299 days for reconstruction of the bridge [1, 2]. According to one of the national surveys conducted amongst 29 states of United States, 18 states cited collisions due to over-height vehicles as a major problem [3].

This thesis follows the style of *Earthquake Engineering and Structural Dynamics*.

To avoid such catastrophic disasters, many states like Mississippi, Indiana, Illinois, Missouri, and Georgia are developing programs to screen the bridges having low vertical clearance and raise the bridge superstructure. The Georgia Department of Transportation (GDOT) has increased the vertical clearance of more than 50 multi-span simply supported (MSSS) and multi-span continuous (MSC) bridges in Georgia by elevating the bearing height using steel pedestals that range in height up to approximately 33½” (0.85 m). These tall pedestals are effective in increasing the vertical clearance, requiring minimal time and easy-to-use technology with synchronized jacks. The installation process is cost effective as well. But since these pedestals are designed without seismic consideration, they may perform poorly similar to high-type steel “rocker” bearings in previous earthquakes. This research aims to address how steel pedestals behave when subjected to a range of ground motions when a nonlinear time history analysis is conducted on a candidate bridge in Georgia modeled using SAP 2000. Another aim of this research is to assess the behavior of these steel pedestals based on their hysteretic behavior obtained experimentally for configurations of key elements of the bridge via parametric studies.

1.2. OBJECTIVES

To examine the seismic effects, a MSSS candidate bridge in Liberty County, Georgia is analytically modeled using force-displacement hysteretic curves of 19” and 33½” steel pedestals that are experimentally obtained [1]. The curves are used to define the nonlinear behavior of the steel pedestals, thereby providing a more realistic representation of the behavior of these bearings. As such, the primary objectives of this study are:

1) To develop a three-dimensional model of a candidate bridge in Liberty County, Georgia using force-displacement hysteretic curves previously obtained from experimentation to uniquely define the nonlinear behavior of various types of steel pedestals.

2) To analyze the effects of various types of earthquake ground motions on the candidate bridge and summarize the displacements and forces exerted on the bearings, connection base, columns and deck gap element. The results from nonlinear time history analyses of these parameters are plotted to reveal the performance of these components.

3) To conduct a parametric study to assess critical components that can affect the seismic performance of a bridge with special bearings (i.e. steel pedestals) such as varying the mass of the structure (using a lightweight concrete deck), varying the stiffness of the deck gap element, varying column heights and addition of cable restrainers for seismic retrofitting.

1.3. THESIS SCOPE AND OUTLINE

The entire thesis has been divided into six major sections. The first section gives the general introduction.

The second section provides an insight of the research that has been done in this area of interest and summarizes their conclusions and important points, which will be useful in this study. It includes the definition of tall bearings, function and purpose of steel pedestals and the past seismic performance of tall bearings either through experimental methods or through analytical modeling.

The third section presents the procedure adopted for modeling the candidate bridge. It includes the various user-friendly features SAP 2000 offers, and their brief description. In addition, it includes the physical description of the candidate bridge, its components and the model development of support conditions, loading, and other assumptions.

The fourth section presents the results of the analysis. It gives the results for the modal analysis and nonlinear time history analyses of the synthetic ground motion data for several low, moderate and high seismic intensity earthquakes. It also presents the verification of the models used for analysis and summaries of the results.

The fifth section is a compilation of the various parametric studies that has been conducted in this research. This includes the effects of variation of key parameters like the usage of lightweight concrete deck leading to reduction of structural mass, variation of the abutment stiffeners, effects of pounding and variation of stiffness of deck gap element, variation of vertical ground accelerations, column heights, effects of boundary conditions and seismic retrofit measures.

The sixth section summarizes all the important results that are derived from this study and the suggestions for improvement of the performance of the elevated bridges.

In the end of the thesis, the references have been provided and additional plots from the parametric studies have been compiled, and tabulated for completeness in the Appendix.

2. LITERATURE REVIEW

2.1. DESCRIPTION OF STEEL PEDESTALS

Steel pedestals have been used in more than 50 bridges in the state of Georgia to increase the vertical clearance, thereby limiting the likelihood of damage to the superstructure that can possibly be caused by over-height vehicles. Steel pedestals can be defined as stubby steel columns consisting of W-shape sections or built-up sections, having 1" top and bottom steel end plates. They are connected to a girder by two anchor bolts, and are attached to the bent cap using a pair of L-shaped angles fixed with slotted holes for anchor bolts. The base plates and angles are welded together and a 1/8" elastomeric bearing pad is placed between the steel pedestal and bent cap for improved flexibility and shear capacity [1]. The height of the steel pedestals for this investigation is classified into two categories: short pedestals (19" in height) and tall pedestals (33½" in height). The two types of steel pedestals are shown in Fig. 2-1 and 2-2.

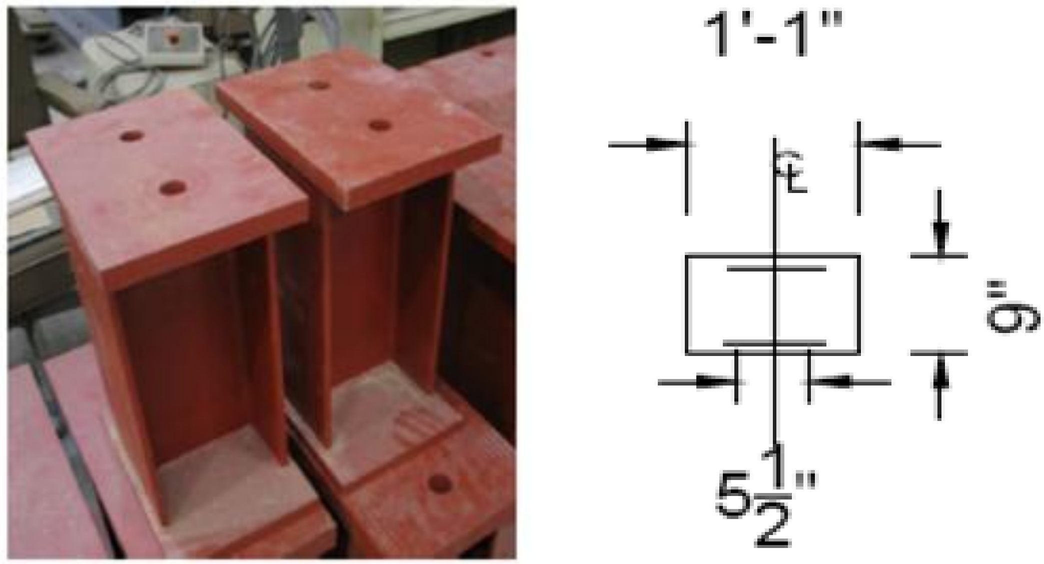


Figure 2-1: 19" tall pedestals with dimensions of the top plate [1]

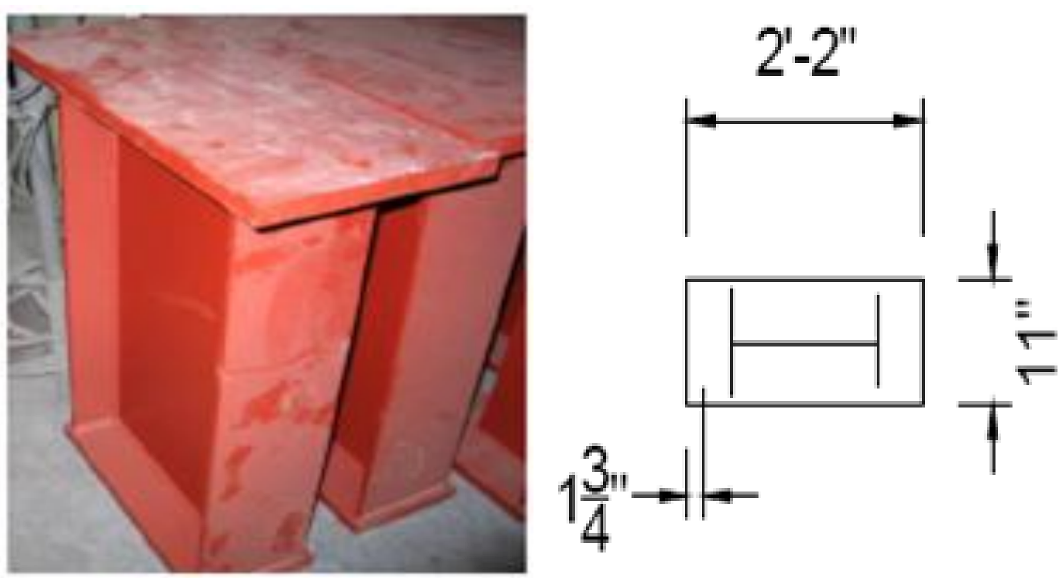


Figure 2-2: 33½" tall pedestal with dimensions of the top plate [1]

2.2. EXPECTED BEHAVIOR OF STEEL PEDESTALS

The expected behavior of the steel pedestals can be estimated by knowing its force-deformation relationship, rigid body kinematics of the pedestals and the deformation modes observed in experimental tests [1]. The force-deformation relationship shows the characteristic hysteresis behavior of the steel pedestals, which is mainly due to three reasons, the bolt slip, sliding of the pedestals over ⅛" elastomeric pad (made of neoprene) and the prying-action due to presence of anchor bolts, which enables the pedestals "rock" about its center of rotation. The sliding and rocking phenomenon of these pedestals characterizes its rigid body kinematics and indicates that these pedestals are indeed very flexible elements. The deformation modes as obtained from experimental testing [1], indicates three modes of possible failure: 1) due to prying-action of bolts, which according to experimental results is the predominant mode of failure, 2) due to shear yielding of the bolts, and 3) due to possible concrete breakout at its edges.

2.2.1. Force-deformation relationships

The force-deformation relationship as obtained by experimental results showed the hysteresis behavior of the pedestals. In the experimental tests conducted [1], a small scale bridge test model was created, and force was applied by means of an actuator on the superstructure in longitudinal direction, and the pedestal configuration was changed so that even the transverse loading situation can be captured. The force was applied until peak deformation was achieved, i.e. beyond which the pedestal setup was bound to fail due to one of the possible deformation modes. Then force in the negative direction or pulling, was applied by the actuator until maximum negative peak deformation is reached. Thus, the cyclic loading of pushing and pulling on the specimen was repeated and continued for a number of cycles. The force-deformation data when plotted showed the hysteresis behavior of these pedestals, as shown in Fig. 2-3 for one of the cases. This hysteresis behavior was mainly due to the slipping of bolts, sliding of pedestals on neoprene pad and the prying-action of the bolts also called rocking. There were some other minor factors too like the initial direction of loading, imperfections at the time of construction of experimental setup, losses due to friction etc. To remove the effect of construction imperfections, each test began with an initial shakedown, i.e. the pedestal setup was given small deformations. These initial shakedown tests also revealed the linear behavior of the pedestals. For higher intensity cyclic loading, the behavior was nonlinear as depicted in the force-deformation relationships. It was also observed that the stiffness of each of the pedestals degraded with increased cycles. The position of the anchor bolts also affected the resistance of the pedestal system and thus response of it. In some cases the location of the center of rotation shifted from the neutral axis leading to unsymmetrical bending, which is also reflected in hysteresis loops of the pedestals tested. The force-deformation behavior indicates the pedestals to be very flexible elements and have high deformation capacity. All the key results of the experiment are summarized in section 2.3.

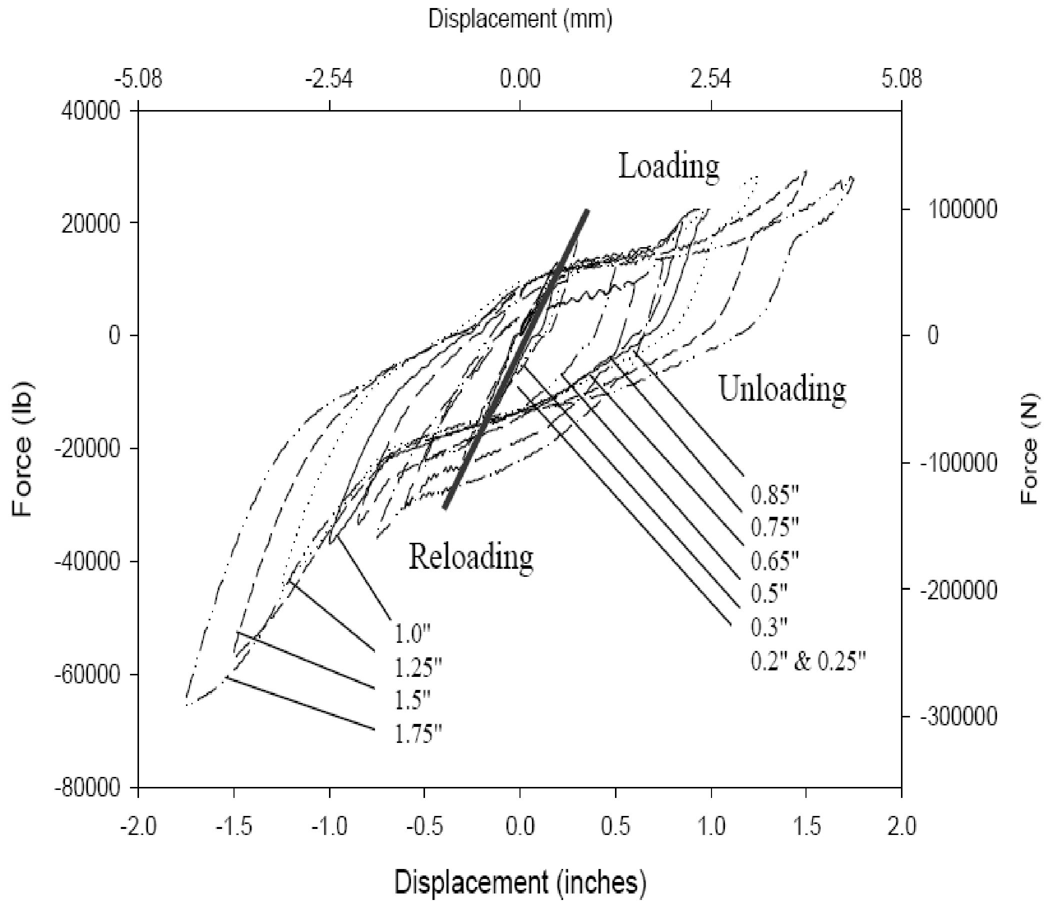


Figure 2-3: Force-deformation plot for P1-1 19" pedestals [1]

2.2.2. Rigid body kinematics

According to the experimental results [1], the main characteristics of the rigid body kinematics of these pedestals are the sliding and the rocking behavior of them as the bolts are being pried from the concrete. It also reaffirms the flexibility that these pedestals possess through bending. When the force applied on the pedestals exceed the linear range then the sliding action starts, which indicate the onset of the nonlinear behavior of them. The onset of sliding action can also be implied when in the force-deformation curve, for little increment of force, large deformations are observed. The sliding is continued until the anchor bolts are engaged, i.e. the anchor bolts try to pull the pedestals back, and the pedestals tend to rock about its center of rotation. The rocking phenomenon is due to the prying-action of the bolts, and in the force-deformation relationships it is indicated by double curvature or the pinching of the hysteresis loop. Energy is dissipated in both these phenomenon. And thus the size of the hysteresis loops keep on decreasing. The sliding and rocking behavior is indicated in Fig. 2-4 and their effect on the hysteresis behavior of the pedestals is shown in Fig. 2-5.

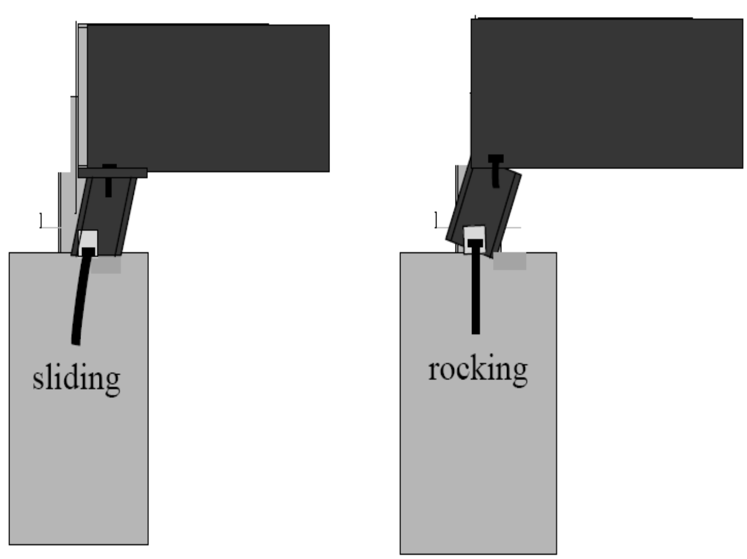


Figure 2-4: Sliding and rocking behavior of pedestals [1]

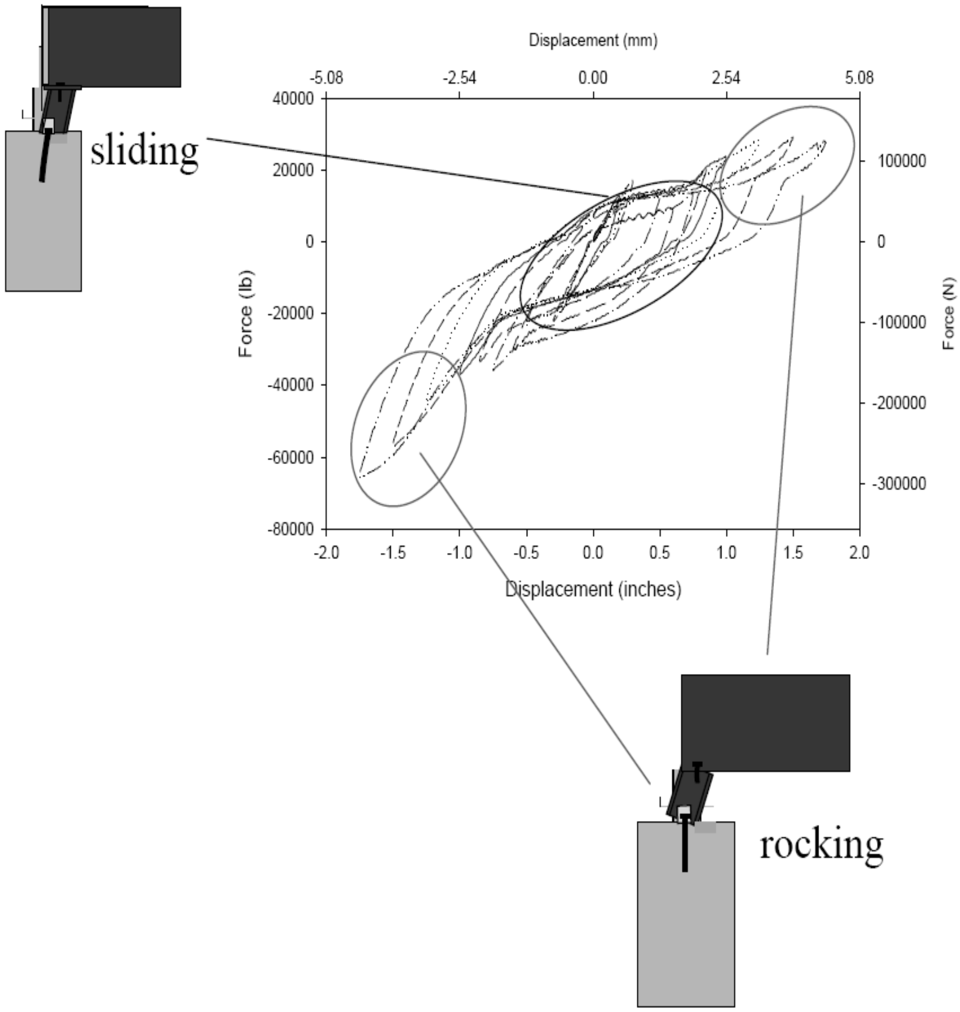


Figure 2-5: Effect of sliding and rocking on hysteresis loop of P1-1 [1]

2.2.3. Deformation modes

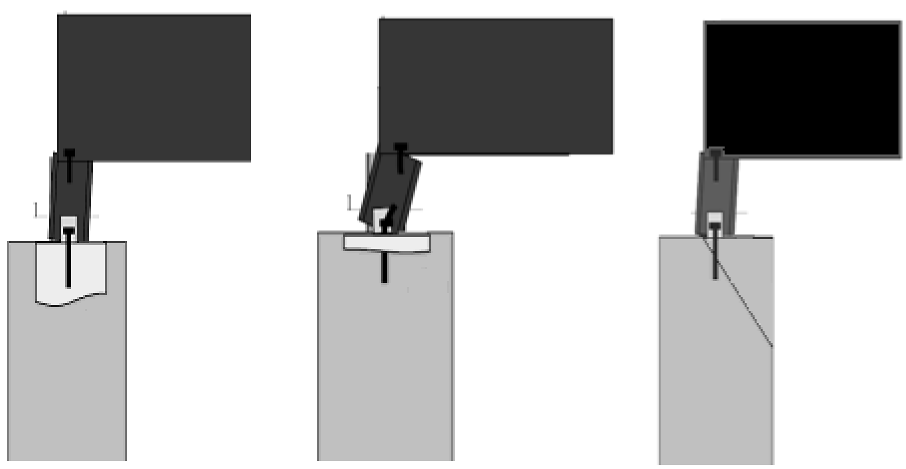
The experimental tests revealed three probable deformation modes that can cause the failure of the pedestal setup:

1) Prying-action of the bolts

2) Shear yielding of the bolts

3) Concrete breakout or failure at the edge.

The prying-action was the predominant mode as per the tests, leading to failure of surface or concrete crushing or the yielding of bolts in some cases. The shear yielding of the bolts were also observed in some cases when the shear forces at these bolts exceeded their shear capacity and the concrete edge break out was observed when the concrete failure occurred before the failure of the bolts. As such, the shear capacity for the analyses of this investigation use the experimental results as the expected capacity of the system due to a deformed mode observed (prior to reaching their ultimate capacities) These possible deformation modes are showed in Fig. 2-6.



a) b) c)

Figure 2-6: Deformation modes prior to reaching ultimate loading [1].
a) Prying-action b) Concrete Crushing c) Concrete breakout

2.3. SUMMARY OF EXPERIMENTAL RESULTS [1]

The maximum force and deformation capacities of these steel pedestals are found out by experimental results [1] and form the basis for comparison with the nonlinear time history analysis results of bridge models. In the experimental study three types of steel pedestals are used : short steel pedestals (P1-1 and 1-2) and two types of tall steel pedestals that have different anchor bolt connection details to the bent cap (P2-1, 3-1 and P2-2, 3-2) shown in Table 2-1. The experimental results for peak deformation and force capacity of these bridge pedestals can be summarized in Table 2-2.

Table 2-1: Steel pedestals used experimental testing [1]

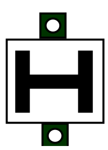
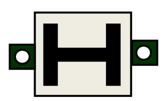
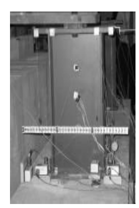
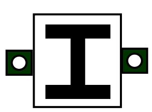
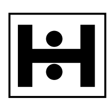
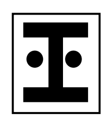
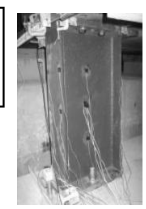
Loading Direction	**Phase 1 (P1)**	**Phase 2 (P2)**	**Phase 3 (P3)**
	Short Pedestals 19” (0.5 m)	**Tall Pedestals 33½” (0.85 m)**	
P →	 P1-1 	 P2-1 	 P3-1 
P →	 P1-2 	 P2-2 	 P3-2 

Table 2-2: Experimental results [1]

SNo.	Pedestal Type	Max. Deformation Capacity (mm)	Max. Force Capacity (kN)	
			Pushing	Pulling
1)	P1-1	± 44.45	125.32	-291.97
2)	P1-2	± 82.55	347.08	-428.40
3)	P2-1	± 35.56	163.54	-136.00
4)	P2-2	± 88.90	242.64	-272.42
5)	P3-1	± 50.90	235.53	-204.42
6)	P3-2	± 50.90	246.20	-237.31

2.4. SIMILARITIES BETWEEN STEEL PEDESTALS AND STEEL BEARINGS

Like typical steel bearings, steel pedestals also serve the purpose of transferring forces from the bridge superstructure to substructure apart from allowing their normal structural movement and supporting them at constant level. Steel bearings can also be classified into two types: 1) high-type bearings, which can be either fixed (pinned) or expansion type (rocker) depending on its connectivity with the bent cap and 2) low type (sliding) bearings. Fig 2.7 shows the high-type steel bearings clearly making a distinction between the fixed (pinned) and expansion (rocker) type.

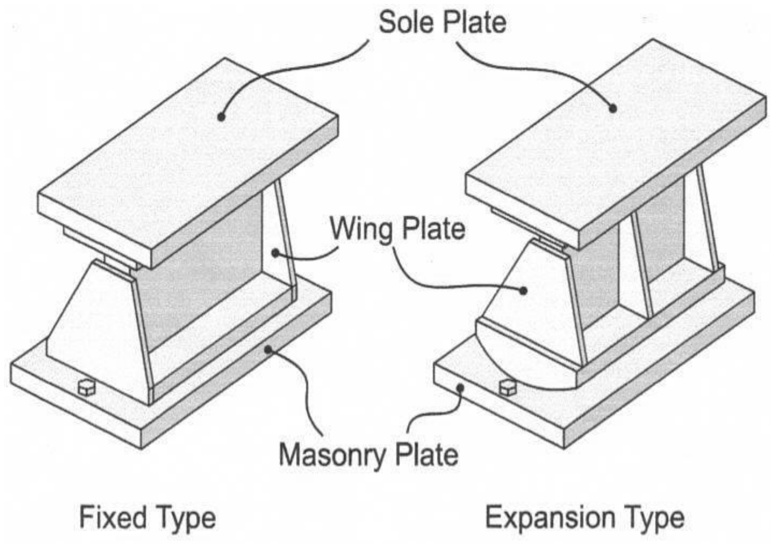


Figure 2-7: High type "rocker" bearings [1]

The high-type bearings consist of heights that are approximately 20.5" (0.52 m) similar to the short steel pedestals [4]. The function of steel bearings is similar to steel pedestals, where they are designed to transfer forces from the bridge superstructure to the substructure. The seismic vulnerability of these steel bearings is explored in the next section. The similarities between the steel bearings and steel pedestals pertaining to their height and their load transfer mechanism suggests that like the steel bearings these steel pedestals may also be found to be vulnerable to seismic loads.

2.5. SEISMIC VULNERABILITY OF HIGH-TYPE "ROCKER" BEARINGS

The forces in these bearings are induced by the vertical load (dead or live) on the superstructure and also by the lateral forces in the transverse direction like seismic forces or wind forces, which induce a moment in the bearing itself. A seismic load that acts in transverse direction leads to a moment inside the bearing that is equivalent to the product of lateral seismic force at top and the height of the bearing. This moment is thus of greater concern when the bearing height is more, i.e., especially in the case of tall bearings.

Past research has shown that high-type “rocker” bearings have been vulnerable to earthquakes, and several MSSS bridges have been damaged in the Guatemala City earthquake in 1976 (Guatemala), Eureka earthquake in 1980 (California, USA), and the Kobe earthquake in 1995 (Japan) [1,5]. The research on these failures concluded that the failures of those MSSS bridges are mainly due to the lack of strength, ductility and stability of the high-type “rocker” bearings. [1, 5-9]. The seismic effects on older bridges were even more critical as observed from, 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, 10]. Much of the research, however, is focused on steel bearings but not steel pedestals.

In recent times, as the Georgia DOT started using the steel pedestals, experimental testing was conducted to provide realistic force-displacement hysteretic curves to capture the nonlinear response and show that the behavior of these steel pedestals was satisfactory for low seismic loads [1]. This research uses those hysteretic curves to predict the system response on how these steel pedestals may perform, where a three-dimensional bridge model is developed such that the critical experimental force-displacement hysteretic curves are explicitly defined. The detailed analytical model includes refined elements, where parametric studies of the critical parameters that affect the seismic performance of steel pedestals are conducted for sensitivity analyses. Furthermore, the analysis of these models can be extended to moderate-to-high seismic loads to gain a better understanding of the seismic behavior of bridge steel pedestals.

3. ANALYTICAL MODELING OF A BRIDGE WITH STEEL PEDESTALS

3.1. INTRODUCTION

SAP 2000 is a finite element software package [11] that provides user-friendly features like graphic user interface and bridge modeler using which any person having basic understanding of structural mechanics and behavior can 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, etc., and even modeling assumptions to represent the deck (as equivalent beam type or shell type), column supports, soil–abutment interaction, restrainers and deck gap elements. Seismic design guidelines are used to accurately model key components of a bridge [12-15].

3.2. ANALYSIS TYPE

This research is based on a nonlinear time history analysis of the bridge. Nonlinear behavior is considered for modeling of the 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. This is because, after certain stress limits, a material approaches its nonlinear regime, and there is a internal redistribution of forces that lead 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 [14]. Six degrees of freedom are used for analysis of the whole structure.

3.3. 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 consists of a concrete slab-on-steel-girder bridge, built circa 1970, and rehabilitated with steel pedestals to increase the vertical clearance 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. The bridge is a steel girder bridge, having total length of 124 m, and skew of 18.5º. The modeling parameters are chosen based on practical considerations and were simplified for ease in application. The bridge wizard feature of SAP 2000 is used for modeling purpose. The three dimensional model of the candidate bridge located in Liberty County, GA is shown in Fig 3.1.

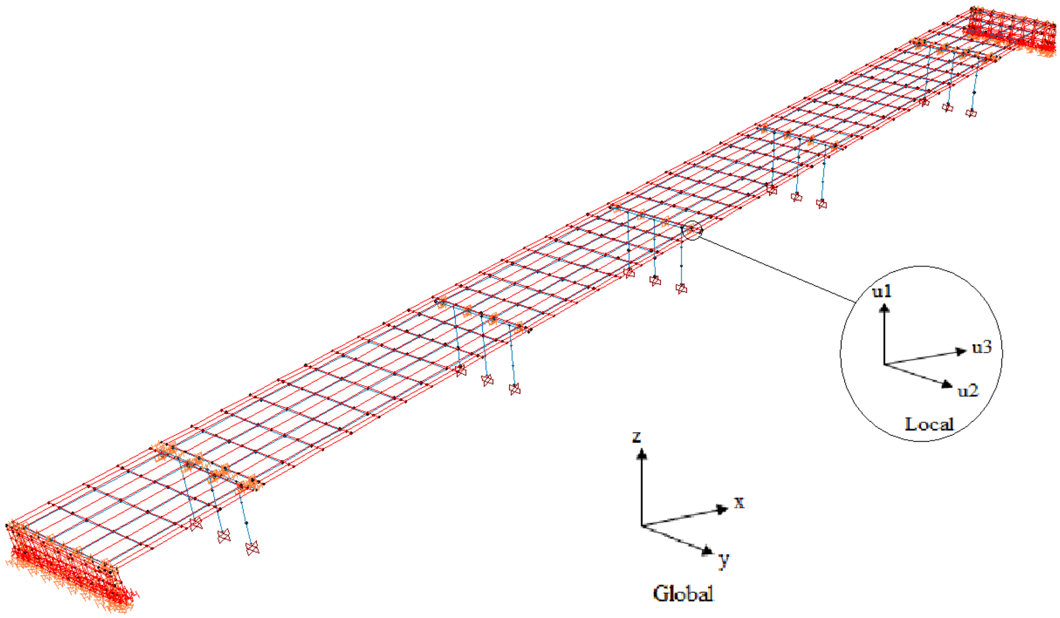


Figure 3-1: Three dimensional view of the candidate bridge

3.4. MODEL GEOMETRY AND FINITE ELEMENT TYPE

The three-dimensional model having frame elements also popularly called a “lumped mass stick model” is used for the seismic analysis of the bridge. This is a common modeling approach, which has been used in many industrial work and research. For any seismic analysis, it is appropriate for the model configuration to 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 the user to define the various geometric features of every component of the bridge including deck, column, abutment, and bent. It also allows the user to define the material properties accordingly based on the section properties, dimensions, and material properties such that the mass of each component is accurately calculated for the entire bridge. In this analysis, the dead load is included, but the live load has been excluded based on past research [12-14, 16].

The distribution of mass depends on number of finite elements used to model any component of a 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. In this research, first hundred modes are considered although the analysis results are displayed for first four modes only.

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 [14, 16].

3.5. MODEL DEVELOPMENT AND ASSUMPTIONS

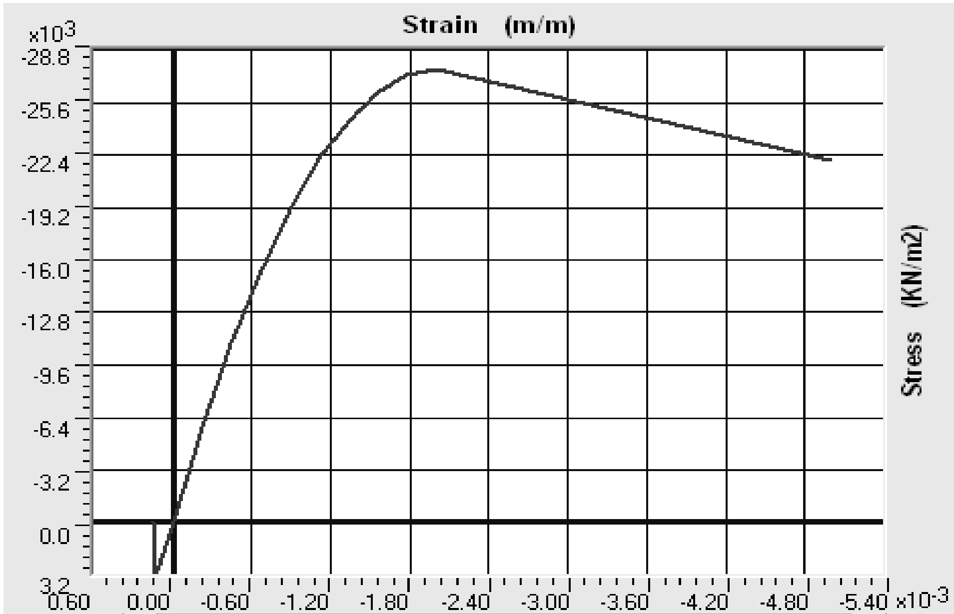
The subsequent sections describe the modeling of each component and the assumptions made. The important features of the bridge can be summarized in Table 3-1.

Table 3-1: Geometric details of the bridge

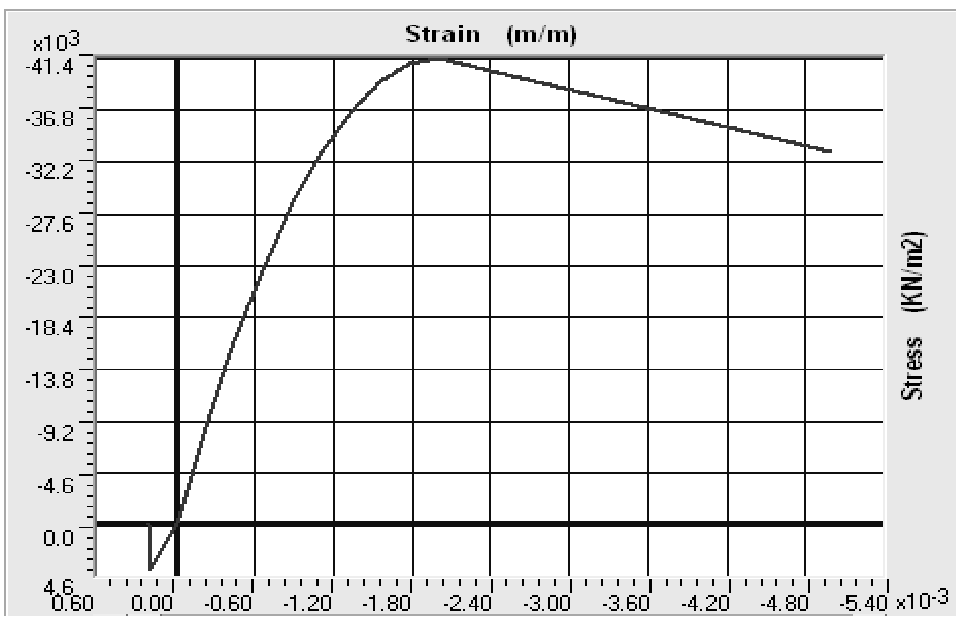
1)	Total length	124 m (406 ft)
2)	Span 1,6	12 m (39 ft)
3)	Span 2,5	28 m (92 ft)
4)	Span 3,4	22 m (72 ft)
5)	Height of column	7 m (23 ft)
2)	Skew	18.25°
3)	Number of column per bent	3
4)	Position of deck gap element	at 12 m (39 ft), 112 m (367 ft)from starting station

3.5.1. 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 nonlinearity associated with it. The bridge modeler has the option of defining the deck section based on the various templates. After choosing the 'concrete slab on steel girder deck' template, the data is modified according to the details of the candidate bridge. The number of finite elements (10 per 3 m length of deck) 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 the unconfined concrete model and 6 ksi for the lightweight concrete model. The material property of both these forms of concrete can be represented by their stress-strain behavior (Fig 3-2). The deck properties are specified in Table 3-2.



a)



b)

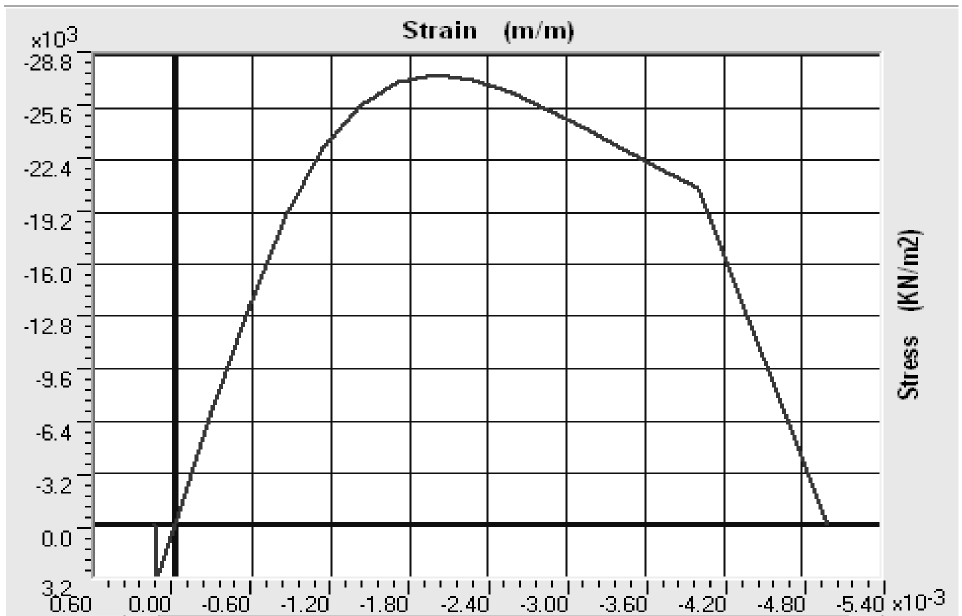
Figure 3-2: Stress-strain relation of a) unconfined concrete (4 ksi) b) lightweight concrete (6 ksi)

Table 3-2: Properties of the deck

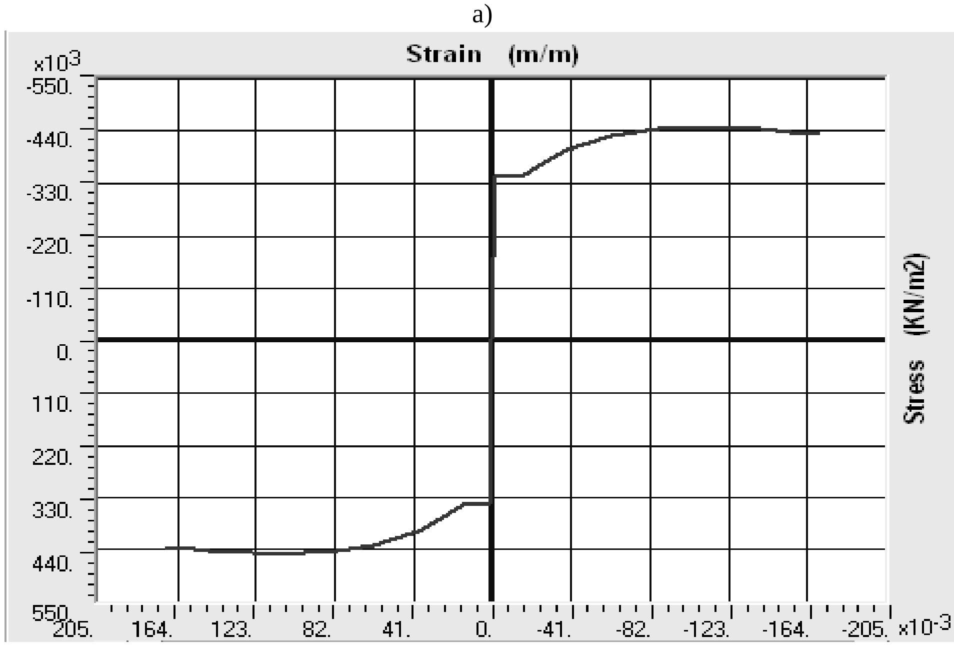
Cross-sectional properties of 8'' concrete slab on steel girder deck (NCS)		
1)	Area of cross section	4.12 m^2 (44.33 ft^2)
2)	Width	10 m (32.8 ft)
3)	Material (concrete)	27.60 MPa (4 ksi)
4)	Moment of inertia	1.04 m^4 (120.41 ft^4)

3.5.2. Columns

The column has been modeled as a nonlinear element, following Mander's confined concrete model [17]. The concrete used is having a compressive strength of 4 ksi (27.60 MPa), and its stress-strain relation is shown in Fig 3-3. 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, where there is a rigid connection to the bent cap. The properties for the columns are specified in Table 3-3. The column has been provided with adequate reinforcement in longitudinal direction and lateral ties for confinement. This is done to prevent yielding and thereby ultimate failure of columns as this research is mainly focused on capturing the behavior of the superstructure, in particular, the steel pedestals.



a)



b)

Figure 3-3: Stress-strain relation of a) confined concrete model (4 ksi) b) reinforcing steel (A992 Fy50)

Table 3-3: Cross-sectional properties of the 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)

3.5.3. Bent caps

The bent caps are also modeled as linear elastic elements. Although only one element is typically enough for modeling of the bent cap but due to number of connections, it is divided into eight number of elements. It's connected with columns and bearings, and is having rigid connection. Where a deck gap element (or bridge expansion joint) is present, it may have a rigid offset too, connecting to the bearing. Both these modifications are shown on page 31. The bent is skewed at an angle of 18.25° with the longitudinal axis of the bridge. The properties for the bent cap are specified in Table 3-4.

Table 3-4: Cross-sectional properties of the bent cap

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)

3.5.4. Steel pedestals

In this study three types of steel pedestals are analyzed based on their heights and the configuration of the anchor bolts that connect them to the bent cap – short steel pedestals (P1-1 and 1-2) and two types of tall steel pedestals that have different anchor bolt connection details to the bent cap (P2-1, 3-1 and P2-2, 3-2) shown in Table 2-1. The steel pedestals are also modeled as nonlinear link elements having multi-step plastic force-deformation and moment curvature relation, which can be easily input 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 force-deformation data is shown in Fig 3-4.

3.5.5. Abutment

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. 3-5. The backwall properties are taken from the bridge plans. The soil stiffness properties are taken from default values available in SAP 2000 software, which are $8.644e^{+08}$ kip/ft ($1.261e^{+10}$ kN/m) in the x, y, and z directions (linear stiffness) and 2.41 e^{+08} kip/ft ($3.514e^{+09}$ kN/m) in r_x, r_y, and r_z directions (rotational stiffness).

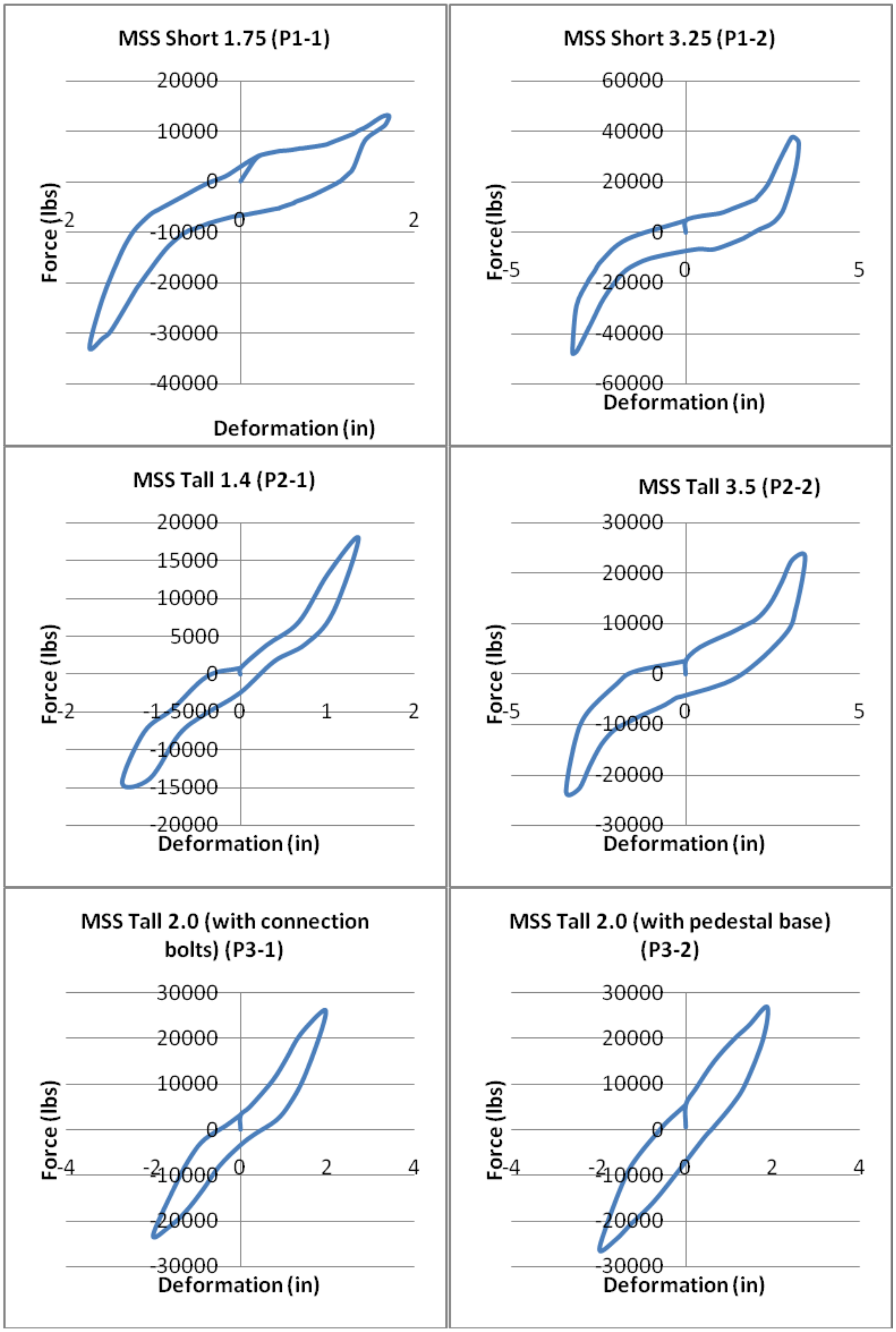


Figure 3-4: Force-deformation data for steel pedestals [1]

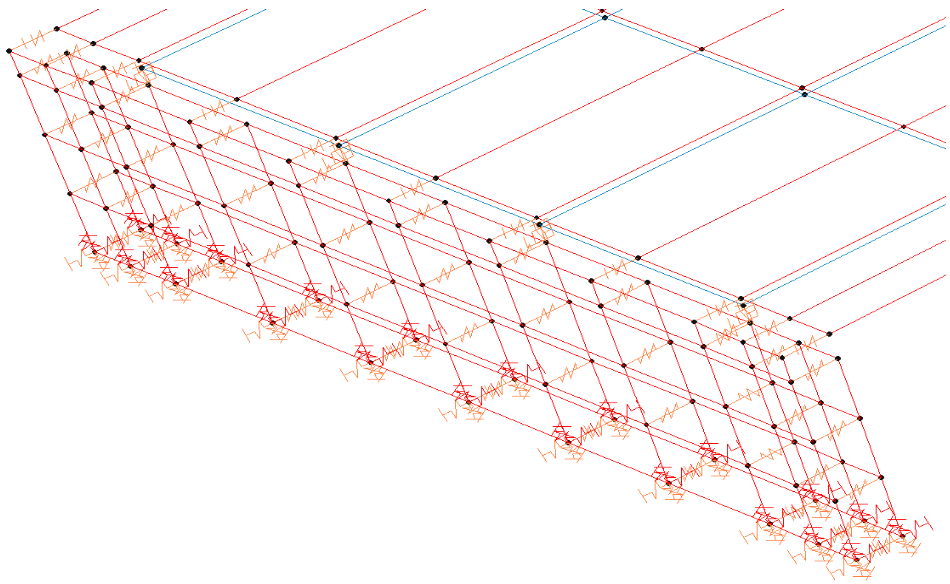
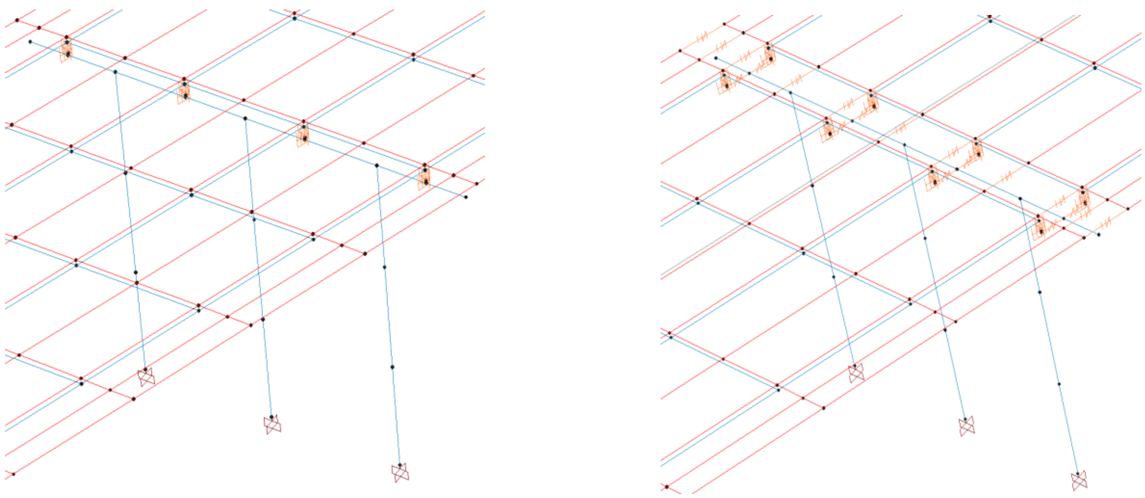


Figure 3-5: Model of abutment

3.5.6. Deck gap element

The nonlinear deck gap element is modeled as a series connection of equivalent stiffness with an initial gap in the longitudinal direction only. The range of the effective stiffness of the deck gap element is generally between 10^3 to 10^6 kN/m [18]. 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). This assumption is made to get the longitudinal mode as the fundamental mode of vibration for the bridge which is a general expected behavior. The deck gap element should not be too stiff that surrounding objects and should be a compression only member. Generally, as a thumb rule the stiffness of the deck gap element should not be 1000 times more than the stiffness of adjacent superstructure [18]. The modeling of the foundation elements, i.e. pile caps and piles, has been excluded from the scope of the current investigation. The location of deck gap element is shown in Fig 3-6.



a) b)

Figure 3-6: Model of bent cap a) without deck gap element b) with deck gap element

3.6. GROUND MOTION DATA USED

This study uses twelve earthquake ground motions. Eight motions are synthetically developed based on the site-specific conditions for Liberty County, Lowndes County and Bartow County located in Georgia; Fort Payne, Alabama and Charleston, South Carolina [1, 19] .The other two ground motions are recorded from earthquakes in the state of California retrieved from the PEER database [20]. These records represent low-to-moderate-to-high intensity earthquakes at various recurrence intervals for 2% (2475-year return period) and 10% (475-year return period) probability of being exceeded. Time history plots of these ground motions are shown in Fig. 3-9.

The state of Georgia lies in a region of low-to-moderate seismic zone, the peak ground acceleration for the central and south eastern United States for 2% and 10 % probability of being exceeded in 50 years is shown in Figure 3-7 and 3-8 respectively

[21]. These maps clearly indicate that some areas of extreme north of Georgia may experience peak ground accelerations of about 0.1 g and 0.43g for the 475-year and 2475-year design earthquake based on the USGS (2008) hazard maps.

The other two earthquakes, which are not part of CSUS, are the 1994 Northridge earthquake and the 1940 Imperial Valley earthquake. These are landmark earthquakes and are included in this study based on their historical significance. The Northridge earthquake occurred on 17^{th} January, 1994, at 4:30 a.m. The epicenter was situated about 30 km N.W. of Los Angeles. The earthquake is the largest of the significant earthquakes that have occurred in the area since the 1971 San Fernando earthquake. It was much more damaging because its epicenter was located in a densely populated area and very strong ground motions were generated. It triggered a very large number of strong motion instruments throughout southern California, providing the most extensive strong motion data for any earthquake to date. Similarly the 1940 Imperial Valley earthquake is the strongest recorded quake to strike the Imperial Valley which caused at least $6 million in direct damage.

In this research study, the ground motions have been categorized based on it PGA. The low level intensity earthquakes are having PGA less than 0.2 g. The moderate level intensity earthquakes are having PGA between 0.2g-0.4g. The high level intensity earthquakes are having PGA over 0.4 g. This categorization is not based on any specific guidelines, but is done to distinguish between the earthquakes and draw inference from the analysis results based on this classification. Based on this criterion, the ground motions used in this study can be classified as:

1) Low Intensity Earthquakes (PGA < 0.2 g)

    a) Lowndes475, GA (PGA=0.02 g)
    b) Lowndes2475, GA (PGA=0.04 g)
    c) Bartow475, GA (PGA=0.05 g)
    d) Liberty475, SC (PGA=0.04 g)
    e) Bartow2475, GA (PGA=0.13 g)
    f) Fort Payne475, AL (PGA=0.1 g)
    g) Charleston475, SC (PGA=0.18 g)

2) Moderate Intensity Earthquakes (0.2g ≤ PGA ≤ 0.4 g)

    a) Liberty2475, SC (PGA=0.2 g)
    b) Fort Payne2475, AL (PGA=0.4 g)
    c) Imperial Valley (El Centro), CA (PGA=0.3 g)

3) High Intensity Earthquakes (PGA > 0.4 g)

    a) Charleston2475, SC (PGA=1.3 g)
    b) Northridge, CA (PGA=0.83 g)

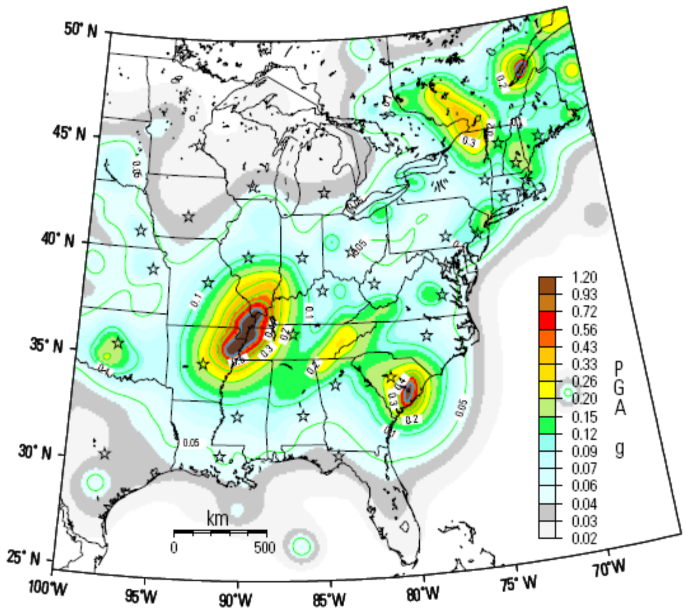


Figure 3-7: USGS (2008) National Seismic Hazard Map (2% probablity of exceedance) [21]

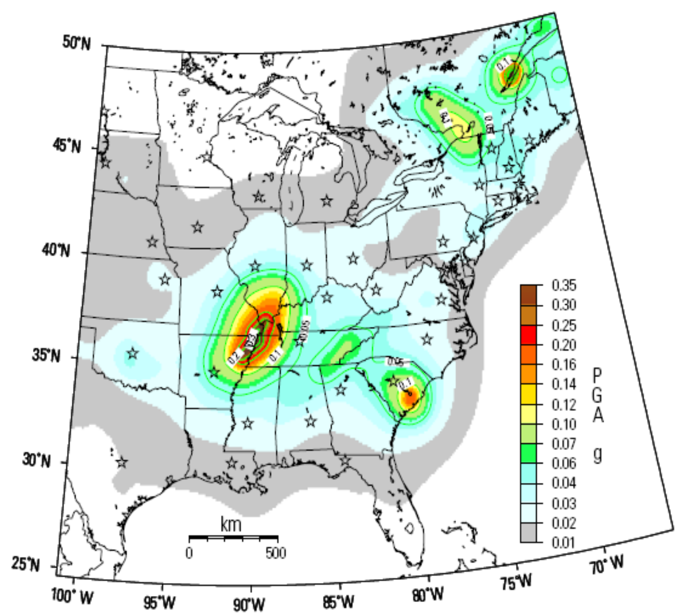


Figure 3-8: USGS (2008) National Seismic Hazard Map (10% probablity of exceedance) [21]

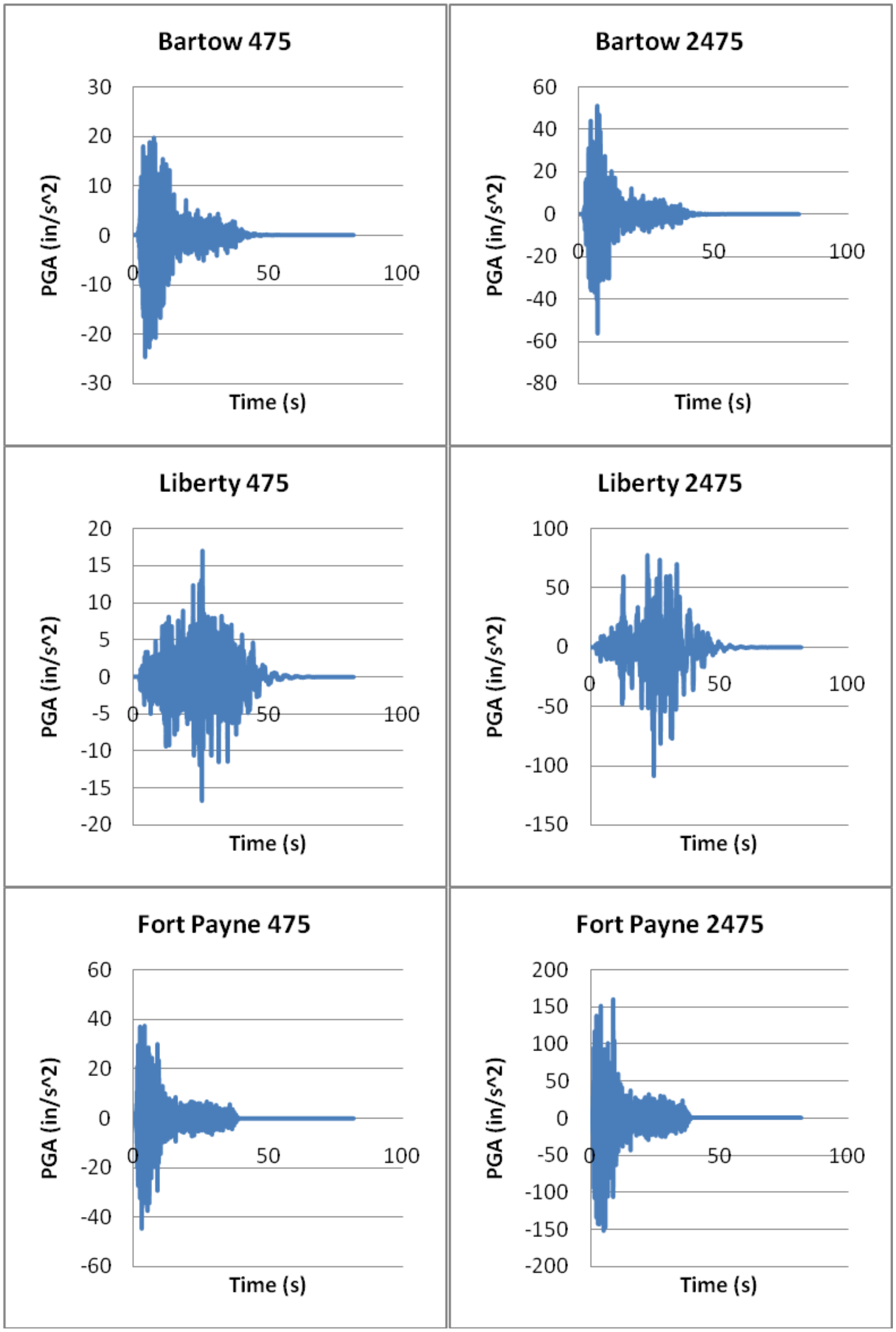


Figure 3-9: Plots of time histories used for analysis

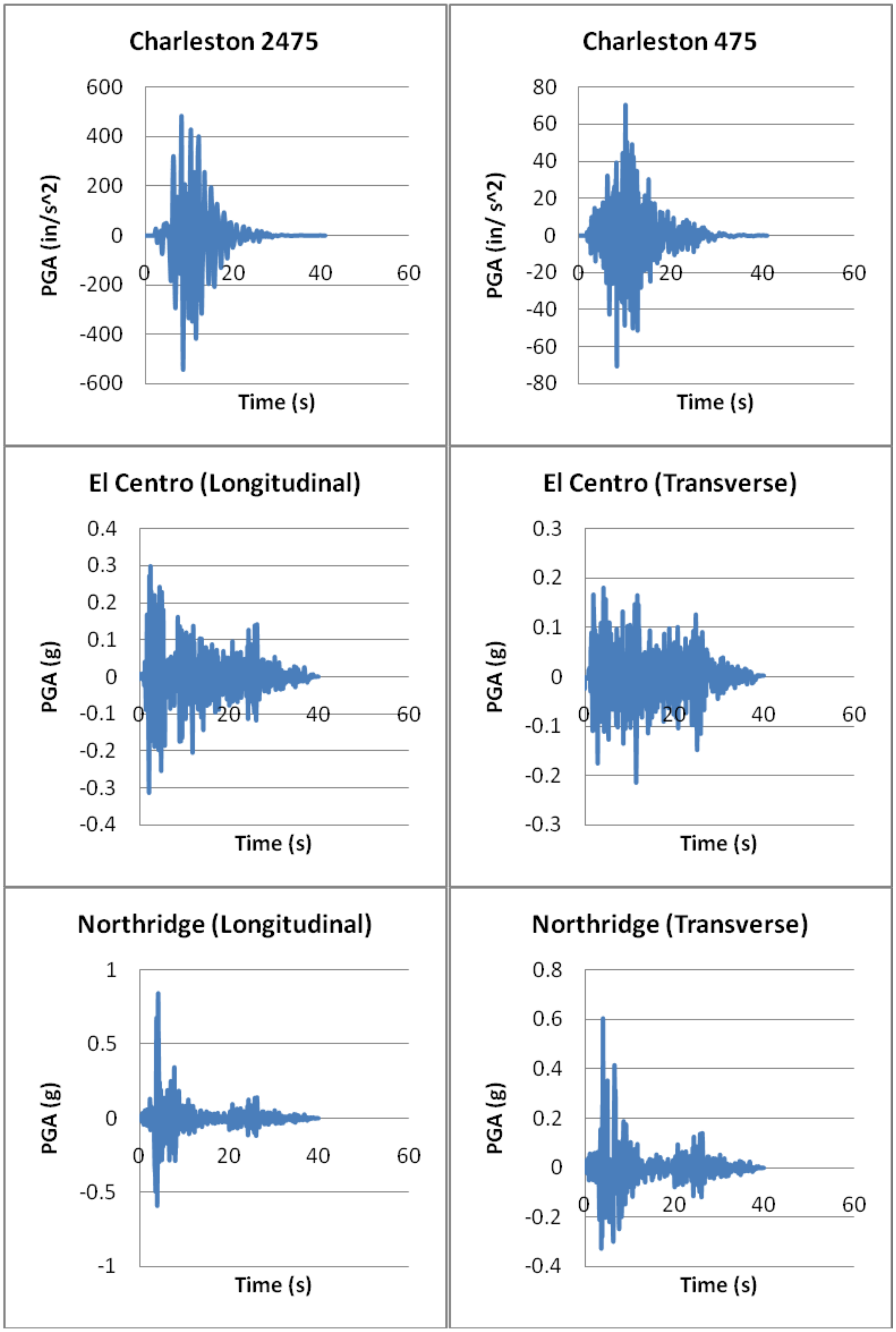


Figure 3-9: Continued

4. ANALYSIS RESULTS OF BASELINE MODELS

4.1. MODAL CHARACTERISTICS OF THE BRIDGE

The time periods of first four modes of vibration for the baseline models is shown in Table 4-1. The fundamental mode of vibration is observed to be primarily a longitudinal mode; the second mode was a transverse mode, in which the end spans remained stationary while the remaining major portion of bridge was vibrating in primarily transverse direction. The third mode was rotational mode and the fourth mode was transverse where end spans vibrated in transverse direction whereas the rest of the bridge remained stationary. In one of the baseline models (NCS P2-2, 3-2), the fundamental mode is transverse instead of longitudinal while third and fourth modes are same as other cases. In the case of the non-skewed bridges the forces in the longitudinal (x) and transverse (y) directions lead to deformation in corresponding x or y direction, i.e. the fundamental mode of vibration is either longitudinal or transverse. But since it is a skewed bridge the forces are induced in both x and y directions and there is a mixture of longitudinal and transverse modes and there is no pure longitudinal or pure transverse mode of vibration [22, 23].

4.2. RESULTS OF NONLINEAR TIME HISTORY ANALYSIS

The results of maximum displacement of pedestals, maximum shear force transmitted to them, their maximum sliding and the pounding analysis of the superstructure are

Table 4-1: Structural period of first four modes (NCS models)

Mode	Time Period (s)		
	NCS P1-1, 1-2	NCS P2-1, 3-1	NCS P2-2, 3-2
1	0.93	0.81	0.94
2	0.82	0.77	0.73
3	0.46	0.43	0.54
4	0.43	0.40	0.49

compiled based on the nonlinear time history analysis of the baseline models. The tables of the analysis results are categorized on the basis of the intensity of the earthquake: low, moderate or high. Each table has maximum and the minimum value of corresponding parameter in both longitudinal (X) and transverse (Y) direction. The maximum shear force is also recorded for both longitudinal (x-x) and transverse (y-y) direction. The results are only shown for the critical bridge components that are selected on the basis of the symmetry of the bridge and the pedestal displacement profile along the bridge length. The displacement profile of the pedestals for a typical case is shown in Fig 4-1. This trend is common for all other cases, and the rest of the results corresponding to other cases are included in the Appendix. Based on the displacement profile, it can be inferred that the behavior of the steel pedestals at the end spans is completely different from the pedestals supporting the rest of the bridge due to the presence of the expansion joint. The expansion joint seemed to disconnect the end spans from the rest of the bridge. This is a general trend observed in all the bridge models including the ones used for parametric studies described in Section 5. The critical bridge components are thus selected so as to capture behavior of the end spans and the rest of the bridge for any parameter under consideration.

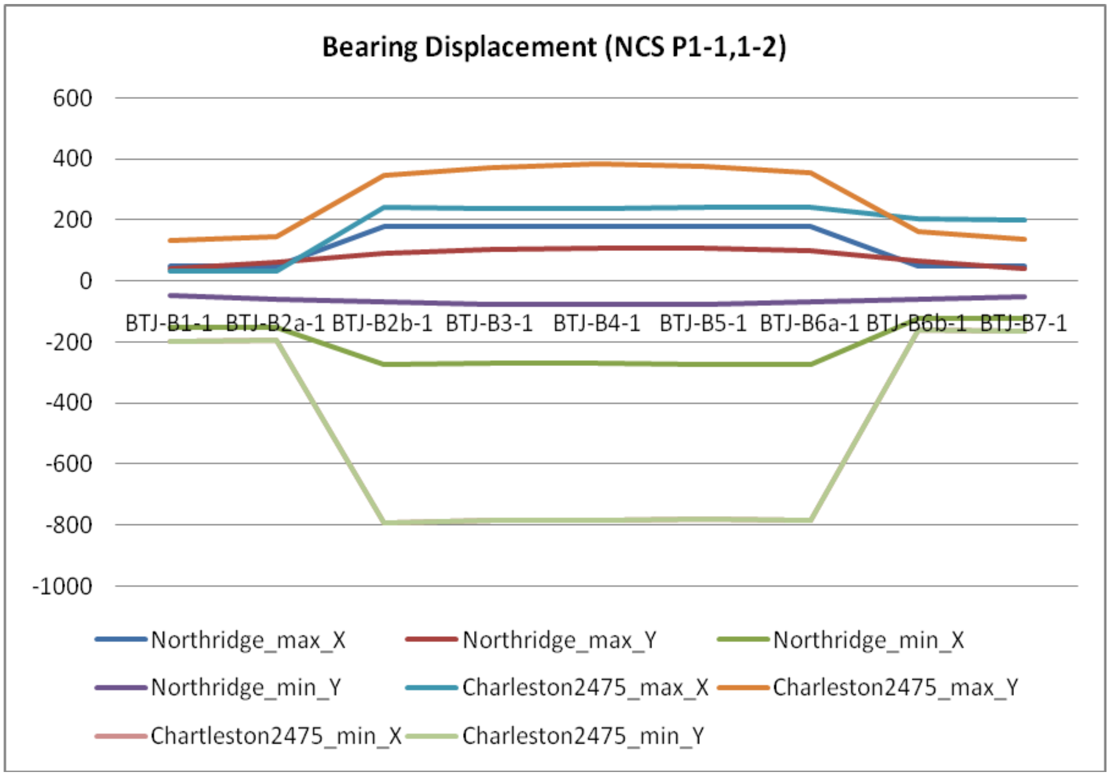


Figure 4-1: Variation of bearing displacement along length of bridge (NCS P1-1, 1-2)

The locations of the critical bridge components to capture maximum displacement of a pedestal are BTJ-2a, BTJ-2b and BTJ-4 (See 'List of Abbreviations and Symbols'). Similarly, the critical bridge components to determine the maximum forces transmitted to pedestals are B-2a, B-2b and B-4. To determine the maximum sliding of pedestals the critical bridge components are TTJ-2a, TTJ-2b and TTJ-3. To find the maximum force transferred to superstructure due to pounding, the critical components are the expansion joints at the abutment and the deck joint (connecting the end spans with the rest of the bridge).

The performance of these pedestals is then assessed on the basis of their capacity-demand ratio ('C/D'). The capacity-demand ratio ('C/D') for any parameter is defined as the ratio between the capacity of the bridge component to the actual demand of the component. The deformation capacity and strength capacity of the pedestals are determined from the experimental results [1], which are summarized in Section 2.3. The sliding capacity is obtained by the seat width provided at the bent cap. The seat width (W) can be defined as the distance between the center line of the pedestal and the edge of the bent cap upon which it is seated. If the displacements due to sliding of the pedestal exceed this seat width, then it will lead to instability of supports and thus unseating of the pedestals. According to MCEER guidelines [15], the sliding allowance should be 60% of the seat width. Based on geometrical drawings the seat width is determined to be 300 mm for the bent caps having an expansion joint and 450 mm for other bent caps. The capacity of the deck gap element used to assess the pounding is the gap of 1" (25 mm) provided. If the gap is exceeded, then pounding occurs. The demand of any bridge component is the corresponding nonlinear time history analysis results compiled in the tables of the analysis results in the following sections. If 'C/D' ratio is less than one, then it indicates that the capacity is less than the demand and thus represents a critical case, which is highlighted using bold fonts in the tables of the analysis results of all the models.

4.2.1. Maximum displacement of pedestals

The maximum displacement of the pedestals is exceeded for the high intensity earthquakes (Northridge and Charleston2475), and also for the moderate intensity earthquakes (Liberty2475 and El Centro). This is indicated by low 'C/D' ratios (less than one) as shown in Tables 4-2-4-4. In fact, the 'C/D' ratios are so low for high intensity earthquakes that they cannot be increased even by retrofitting the whole structure using cable restrainers, which will be later shown in Section 5.4. However, the behavior of these pedestals is adequate for low intensity earthquakes and for moderate intensity earthquake Fortpayne2475. The odd behavior of the pedestals remaining safe for moderate intensity earthquake Fortpayne2475 is because the frequency content of the ground motion does not coincide with the frequency of the structure. This is a common trend observed for the response of the bridge components for most cases in the baseline models and the models used for parametric studies.

Based on the analysis results it can also be observed that the displacement of the pedestal configuration P2-2, 3-2 is lower than that of P2-1, 3-1 and P1-1, 1-2. This shows that the displacement capacity of the configuration P2-2, 3-2 is better than P2-1, 3-1 and P1-1, 1-2. The reason behind it is in P2-2, 2-2 configuration the connecting bolts are located very near to the pedestals reducing the eccentricity from the centerline of the pedestals and are thus effectively utilized to keep the pedestals in their original position. It also shows that the connection details play a major role in the response of the bridge component.

Table 4-2: Maximum displacement of pedestals NCS P1-1, 1-2

Ground Motion	**Type**	**BTJ-2a**		**BTJ-2b**		**BTJ-4**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	2.45	1.69	8.15	4.25	8.14	4.89	5.45	16.88
Lowndes475	Min	-1.7	-3.9	-4.94	-8.99	-5.06	-10.33	8.78	7.99
Lowndes2475	Max	4.26	4.62	12	7	11.96	8.22	3.70	10.04
Lowndes2475	Min	-3.17	-11.39	-7.67	-13.81	-7.88	-15.84	5.64	5.21
Liberty475	Max	4.55	3.75	12.29	6.75	12.24	7.95	3.62	10.38
Liberty475	Min	-3.33	-8.57	-7.6	-13.86	-7.83	-15.72	5.68	5.25
Bartow475	Max	7.28	4.27	16.03	11.04	16.09	13.99	2.76	5.90
Bartow475	Min	-4.6	-8.64	-10.18	-17.07	-10.25	-19.8	4.34	4.17
Fortpayne475	Max	4.6	2.72	8.04	4.21	8.08	4.73	5.50	17.45
Fortpayne475	Min	-2.62	-5.74	-4.51	-6.33	-4.7	-6.8	9.46	12.14
Bartow2475	Max	13.77	8.97	19.58	14.87	19.72	17.06	2.25	4.84
Bartow2475	Min	-14.2	-18.4	-12.79	-19.32	-13.01	-23.19	3.13	3.56
Charleston475	Max	13.9	11.67	25.52	20.1	25.9	23.48	1.72	3.52
Charleston475	Min	-12.55	-18.74	-36.9	-23.69	-37.1	-26.83	1.20	3.08
Moderate Intensity Earthquakes									
Liberty2475	Max	17.07	34.39	74.4	54.5	75.07	62.86	**0.59**	1.31
Liberty2475	Min	-38.56	-31.79	-100.92	-44.71	-101.53	-50.95	**0.44**	1.62
El Centro	Max	19.45	30.62	56.43	53.01	56.39	61.78	**0.79**	1.34
El Centro	Min	-40.56	-31.5	-90.38	-36.72	-90.13	-37.95	**0.49**	2.18
Fortpayne2475	Max	11.11	10.13	18.18	12.07	18.47	14.53	2.41	5.68
Fortpayne2475	Min	-8.07	-14.24	-16.99	-17.07	-17.17	-19.15	2.59	4.31
High Intensity Earthquakes									
Northridge	Max	49.95	61.22	180.02	91.96	178.96	109.06	**0.25**	**0.76**
Northridge	Min	-152.5	-57.58	-272.69	-67.12	-270.72	-75.1	**0.16**	1.10
Charleston2475	Max	30.71	142.3	242.82	342.62	239	382.27	**0.18**	**0.22**
Charleston2475	Min	-194.03	-66.73	-792.62	-158.21	-782.24	-182.99	**0.06**	**0.45**

Table 4-3: Maximum displacement of pedestals NCS P2-1, 3-1

Ground Motion	**Type**	**BTJ-2a**		**BTJ-2b**		**BTJ-4**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	7.04	1.57	14.33	3.76	14.15	4.38	2.48	11.60
Lowndes475	Min	-0.81	-0.86	-4.82	-3	-4.89	-3.88	7.27	13.09
Lowndes2475	Max	12.93	3.77	13.86	5.43	13.63	6.55	2.57	7.76
Lowndes2475	Min	-3.08	-3.83	-4.42	-7.96	-4.58	-8.99	7.76	5.65
Liberty475	Max	13.3	2.61	13.49	3.9	13.27	4.94	2.64	10.28
Liberty475	Min	-5.21	-2.98	-4.47	-8.07	-4.56	-9.25	6.83	5.49
Bartow475	Max	13.26	3.3	19.71	5.79	19.57	6.34	1.80	8.01
Bartow475	Min	-7.83	-5.93	-9.5	-10.34	-9.64	-11.93	3.69	4.26
Fortpayne475	Max	11.43	2.58	13.39	3.83	13.18	4.74	2.66	10.72
Fortpayne475	Min	-1.04	-2.93	-4.74	-4.25	-4.88	-5.38	7.29	9.44
Bartow2475	Max	15.01	7.57	17.53	8.89	17.56	11.49	2.03	4.42
Bartow2475	Min	-8.35	-13.88	-7.83	-10.54	-7.94	-12.66	4.26	3.66
Charleston475	Max	15.65	10.84	31.23	21.1	31.44	23.76	1.13	2.14
Charleston475	Min	-12.87	-13.14	-25.75	-21.61	-26.01	-24.54	1.37	2.07
Moderate Intensity Earthquakes									
Liberty2475	Max	22.36	23.82	56.32	34.95	56.95	41.19	**0.62**	1.23
Liberty2475	Min	-15.92	-18.7	-50.87	-50.54	-51.79	-56.67	**0.69**	**0.90**
El Centro	Max	21.86	20.58	52.03	34.76	51.57	42.12	**0.68**	1.21
El Centro	Min	-18.08	-17.96	-43.97	-27.87	-44.05	-32.8	**0.81**	1.55
Fortpayne2475	Max	18.46	5.27	24.09	10.46	24.17	12.39	1.47	4.10
Fortpayne2475	Min	-8.4	-9.74	-13.06	-14.15	-13.02	-16.22	2.72	3.13
High Intensity Earthquakes									
Northridge	Max	38.02	30.19	121.91	33.68	122.08	38.7	**0.29**	1.31
Northridge	Min	-63.88	-40.69	-211.77	-82.59	-212.28	-92	**0.17**	**0.55**
Charleston2475	Max	90.35	110.16	228.98	203.28	236.59	239.62	**0.15**	**0.21**
Charleston2475	Min	-120.63	-87.48	-337.65	-258.96	-338.9	-293.1	**0.10**	**0.17**

Table 4-4: Maximum displacement of pedestals NCS P2-2, 3-2

Ground Motion	**Type**	**BTJ-2a**		**BTJ-2b**		**BTJ-4**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	7.45	0.81	13.88	0.9	13.68	0.92	6.40	55.22
Lowndes475	Min	-0.88	-0.25	-3.81	-0.63	-3.92	-0.95	22.68	53.47
Lowndes2475	Max	13.19	0.97	12.55	2.23	12.35	2.5	6.74	20.32
Lowndes2475	Min	-4.42	-0.45	-3.82	-2.5	-3.87	-2.86	20.11	17.76
Liberty475	Max	11.19	0.61	12	1.02	11.8	1.43	7.41	35.52
Liberty475	Min	-1.67	-0.39	-3.65	-2.32	-3.7	-2.86	24.02	17.76
Bartow475	Max	11.32	1.18	20.97	1.14	20.81	1.76	4.24	28.86
Bartow475	Min	-2.98	-1.48	-8.69	-4.7	-8.72	-5.78	10.19	8.79
Fortpayne475	Max	10.33	0.55	11.9	0.71	11.59	1.12	7.47	45.36
Fortpayne475	Min	-1.12	-1.43	-3.95	-2.45	-4.09	-3.09	21.73	16.44
Bartow2475	Max	16	1.3	16.79	6.5	16.54	7.6	5.29	6.68
Bartow2475	Min	-3.67	-4.15	-6.88	-7.66	-6.98	-9.1	12.73	5.58
Charleston475	Max	17.83	3.42	35.95	12.64	35.9	14.83	2.47	3.43
Charleston475	Min	-7.33	-3.79	-21.93	-14.56	-22.21	-15.9	4.00	3.19
Moderate Intensity Earthquakes									
Liberty2475	Max	27.09	12.58	57.92	40.18	58.27	44.16	1.53	1.15
Liberty2475	Min	-10.32	-11.19	-45.79	-48.08	-46.54	-54.38	1.91	**0.93**
El Centro	Max	28.92	8.58	53.29	44.86	52.78	50.93	1.67	**1.00**
El Centro	Min	-13.35	-7.24	-36.12	-19.69	-36.31	-25.07	2.45	2.03
Fortpayne2475	Max	19.28	1.25	21.81	6.78	21.55	8.11	4.08	6.26
Fortpayne2475	Min	-4.96	-5.59	-10.15	-6.57	-10.09	-7.34	8.76	6.92
High Intensity Earthquakes									
Northridge	Max	33.32	19.19	107.21	58.08	107.6	65.82	**0.83**	**0.77**
Northridge	Min	-55.3	-49.87	-195.37	-95.01	-194.21	-107.17	**0.45**	**0.47**
Charleston2475	Max	79.05	163.54	221.88	548.94	224.29	603.5	**0.40**	**0.08**
Charleston2475	Min	-101.53	-131.35	-342.84	-305.25	-340.09	-343.23	**0.26**	**0.15**

4.2.2. Maximum force transmitted to pedestals

The maximum force transmitted to the pedestals is exceeded for the high intensity earthquakes (Northridge and Charleston2475). This is indicated by low ‘C/D’ ratios (less than one) as shown in Tables 4-5-4-7. However, the behavior of these pedestals is adequate for low and moderate intensity earthquakes. Hence, based on the results of the previous section, the force capacity of these pedestals is better than their displacement capacities. Here also the ‘C/D’ ratios are so low for high intensity earthquakes that they cannot be increased by retrofitting using cable restrainers (shown in Section 5.4).

It can also be observed that the force transmitted to the pedestal configuration P2-2, 3-2 is relatively higher than that of P2-1, 3-1 and P1-1, 1-2. This is expected behavior, since they have high displacement capacity, they are stiffer than other pedestals configurations and attract more force.

Table 4-5: Maximum force transmitted to pedestals NCS P1-1, 1-2

Ground Motion	**Type**	**B-2a**		**B-2b**		**B-4**		**Max. 'C/D' ratio**	
		Shear (y-y)	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Y-Y**	**X-X**
Low Intensity Earthquakes									
Lowndes475	Max	5.08	5.2	13.71	13.05	13.6	14.68	25.32	8.54
Lowndes475	Min	-1.88	-2.06	-9.39	-4.41	-9.78	-6.2	43.80	47.09
Lowndes2475	Max	13.76	14.61	23.4	20.76	20.46	23.71	14.83	5.29
Lowndes2475	Min	-4.76	-5.94	-13.68	-6.9	-14.24	-11.07	30.08	26.37
Liberty475	Max	11.89	12.81	22.05	19.89	21.07	23.45	15.74	5.34
Liberty475	Min	-5.86	-4.32	-14.35	-6.84	-14.99	-9.6	28.58	30.41
Bartow475	Max	18.94	12.36	28.17	24.98	28.23	27.33	12.29	4.59
Bartow475	Min	-8.13	-4.54	-19.3	-8.48	-19.47	-16.35	22.00	17.86
Fortpayne475	Max	10.23	8.11	14.19	12.15	16.66	15.63	20.83	8.02
Fortpayne475	Min	-4.79	-3.09	-8.98	-3.02	-9.32	-4.05	45.97	72.09
Bartow2475	Max	29.37	22.82	28.75	26.31	29.33	28.84	11.82	4.35
Bartow2475	Min	-17.39	-8.89	-26.97	-12.15	-29.65	-22.69	14.45	12.87
Charleston475	Max	29.07	25.09	37.43	28.76	41.19	30.75	8.43	4.08
Charleston475	Min	-18.89	-10.73	-41.79	-15.4	-44.63	-25.49	9.60	11.45
Moderate Intensity Earthquakes									
Liberty2475	Max	36.54	33.85	108.49	60.32	113.46	81.61	3.06	1.54
Liberty2475	Min	-33.37	-21.32	-96.02	-57.45	-101.6	-112.02	4.22	2.61
El Centro	Max	40.6	33.95	96.67	60.04	113.46	81.58	3.06	1.54
El Centro	Min	-29.11	-25.85	-81.68	-55.19	-92.57	-110.05	4.63	2.65
Fortpayne2475	Max	28.02	24.41	30.07	24.88	30.07	27.2	11.54	4.61
Fortpayne2475	Min	-12.89	-7.74	-23.71	-9.04	-26.02	-15.76	16.46	18.53
High Intensity Earthquakes									
Northridge	Max	113.46	66.36	113.46	100.84	113.46	135.97	3.06	**0.92**
Northridge	Min	-81.53	-130.96	-170.81	-165.86	-184.21	-228.61	2.33	1.28
Charleston2475	Max	113.46	130.07	113.46	369.81	113.46	475.07	3.06	**0.26**
Charleston2475	Min	-32.53	-142.06	-224.69	-702.94	-247.45	-830.6	1.73	**0.35**

Table 4-6: Maximum force transmitted to pedestals NCS P2-1, 3-1

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	11.81	6.08	8.04	2.53	12.33	8.97	19.10	18.23
Lowndes475	Min	-0.44	-12.58	-0.46	-10.5	-7.51	-13.54	27.22	10.04
Lowndes2475	Max	11.98	10.76	11.45	6.36	11.29	15.9	19.66	10.29
Lowndes2475	Min	-0.78	-17.28	-1.11	-13.68	-8.5	-19.48	24.05	6.98
Liberty475	Max	12.26	11.91	12.59	5.08	11.69	13.87	18.71	11.79
Liberty475	Min	-2.32	-17.61	-1.17	-12.71	-7.31	-19.47	27.96	6.99
Bartow475	Max	15.76	12.61	14.48	7.62	18.24	14.76	12.91	11.08
Bartow475	Min	-14.44	-19.09	-3.21	-15.46	-21.99	-22.81	9.30	5.96
Fortpayne475	Max	11.93	6.96	9.19	4.65	11.58	11.34	19.74	14.42
Fortpayne475	Min	-0.55	-13.88	-0.97	-12.41	-6.23	-15.28	32.81	8.90
Bartow2475	Max	15.28	17.6	15.58	15.39	23.66	21.27	9.95	7.69
Bartow2475	Min	-8.35	-19.59	-5.15	-22.17	-21.64	-26.7	9.45	5.09
Charleston475	Max	48.21	33.27	18.1	18.96	50.44	52.45	4.67	3.12
Charleston475	Min	-49.4	-30.42	-8.34	-19.52	-62.14	-42.44	3.29	3.20
Moderate Intensity Earthquakes									
Liberty2475	Max	87.82	70.47	32.92	30.68	100.73	81.08	2.34	2.02
Liberty2475	Min	-88.31	-78.08	-13.84	-24.84	-97.51	-102.09	2.10	1.33
El Centro	Max	84.23	72.28	46.31	31.08	93.07	85.54	2.53	1.91
El Centro	Min	-89.45	-50.64	-24.9	-25.48	-117.06	-71.28	1.75	1.91
Fortpayne2475	Max	19.15	17.94	15.84	13.4	23.73	23.74	9.93	6.89
Fortpayne2475	Min	-15.68	-21.83	-5.89	-19	-37.1	-28.23	5.51	4.82
High Intensity Earthquakes									
Northridge	Max	195.86	82.68	85.73	60.65	241.5	78.21	**0.98**	1.98
Northridge	Min	-248.85	-112.62	-61.92	-54.44	-270.25	-159.11	**0.76**	**0.85**
Charleston2475	Max	266.33	304.22	113.27	163.08	331.92	421.64	**0.71**	**0.39**
Charleston2475	Min	-475.54	-366.87	-100.7	-86.44	-568.33	-498.74	**0.36**	**0.27**

Table 4-7: Maximum force transmitted to pedestals NCS P2-2, 3-2

Ground Motion	**Type**	**B-2a**		**B-2b**		**B-4**		**Max. 'C/D' ratio**	
		Shear (y-y)	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Y-Y**	**X-X**
Low Intensity Earthquakes									
Lowndes475	Max	8	3.28	12.55	6.88	10.62	6.67	19.62	35.27
Lowndes475	Min	-0.01	-10.52	-2.93	-12.23	-8.86	-12.02	26.78	22.27
Lowndes2475	Max	15.3	5.67	13.06	13.4	12.1	14.04	16.09	17.28
Lowndes2475	Min	-2.55	-12.11	-1.53	-13.15	-6.83	-13	34.75	20.72
Liberty475	Max	10.26	6.17	10.88	11.49	11.16	11.75	22.06	20.65
Liberty475	Min	-0.46	-11.99	-1.21	-13.45	-5.08	-13.38	46.71	20.25
Bartow475	Max	9.73	9.28	21.75	12.29	25.92	12.91	9.50	18.79
Bartow475	Min	-0.33	-12.8	-13.17	-14.99	-24.76	-15.98	9.58	17.05
Fortpayne475	Max	7.8	8.81	11.25	10.9	11.94	10.98	20.62	22.10
Fortpayne475	Min	0	-13.18	-0.62	-13.73	-4.61	-13.49	51.48	19.84
Bartow2475	Max	14.38	10.93	18.2	17.02	24.61	18.35	10.00	13.22
Bartow2475	Min	-7.05	-14.52	-8.8	-19.95	-23.98	-21.73	9.90	12.54
Charleston475	Max	22.8	14.75	48.17	22.53	46.56	25	5.11	9.71
Charleston475	Min	-6.91	-14.39	-45.38	-24.3	-56.04	-25.3	4.23	10.77
Moderate Intensity Earthquakes									
Liberty2475	Max	35.53	20.25	96.14	37.08	106.68	40.46	2.31	6.00
Liberty2475	Min	-11.23	-18.61	-108.77	-45.56	-118.1	-54.27	2.01	5.02
El Centro	Max	40.09	17.73	82.12	39.41	101.48	45.17	2.43	5.37
El Centro	Min	-14.29	-16.36	-94.2	-32.64	-149.46	-36.05	1.59	7.56
Fortpayne2475	Max	18.79	12.05	29.94	17.04	33.08	19.76	7.44	12.28
Fortpayne2475	Min	-10.2	-15.85	-15.96	-17.06	-33.5	-19.58	7.08	13.91
High Intensity Earthquakes									
Northridge	Max	72.4	27.88	214.73	60.85	250.33	70.97	**0.98**	3.42
Northridge	Min	-29.15	-42.37	-279.33	-119.04	-266.33	-155.63	**0.85**	1.75
Charleston2475	Max	114.8	122.5	327.26	271.72	374.18	309.58	**0.66**	**0.78**
Charleston2475	Min	-149.62	-134.99	-665.56	-444.35	-564.65	-540.19	**0.17**	**0.39**

The hysteresis behavior of these pedestals is indicated by the force-deformation plots for two typical cases as shown in Fig. 4-2 and 4-3. Since it is a dynamic analysis, not much can be inferred from these plots but they do show the hysteresis behavior of the pedestals and how much energy is being dissipated. From Fig. 4-2 which is for the bearing seated on the bent cap located at the middle of the bridge (B4-1) it can be inferred that corresponding to Charleston2475 earthquake (PGA of 1.3 g) there is a substantial amount of incremental displacement corresponding to little increase in force, which shows the degradation of stiffness with increased cycling and also depicts the sliding behavior of the pedestals. Whereas, from Fig. 4-3, which is a bi-linear force-deformation curve for bearing seated at the abutment (B1-1), it can be inferred that corresponding to Lowndes475 earthquake (PGA of 0.02 g), the pedestals remain in elastic zone and do not show hysteretic behavior. The force deformation plots for remaining cases of baseline models for the high intensity earthquakes Charleston2475 and Northridge are included in the Appendix.

4.2.3. Maximum sliding of pedestals

The ‘C/D’ ratios are having safe values for all the cases as indicated in Tables 4-8-4-10. The seat width (W) is 450 mm for the bent cap having no expansion joint and 300 mm for the bent cap having expansion joint based on the geometric drawings of the candidate bridge. Hence sliding seems to not be of much concern provided adequate seat width (W) is available.

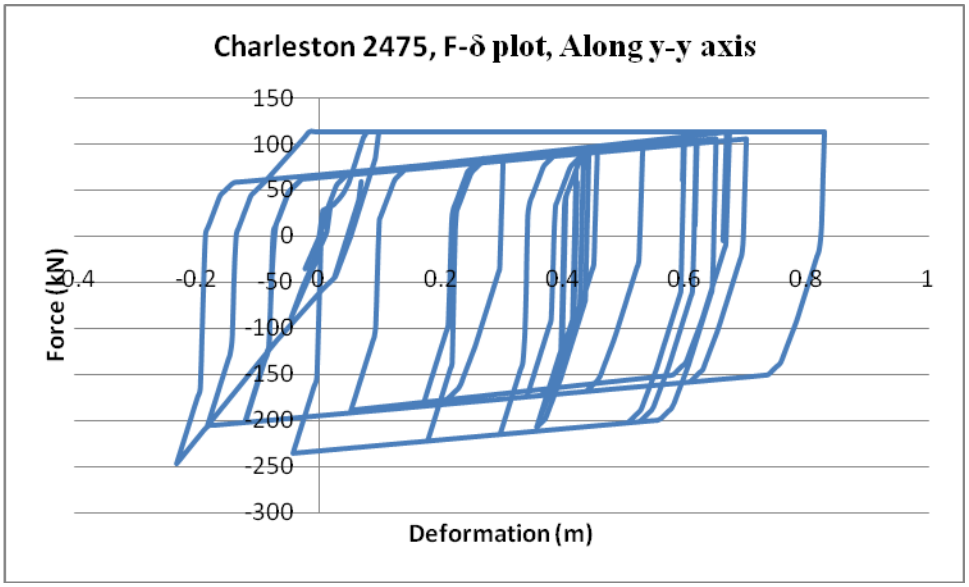


Figure 4-2: Force-deformation (hysteresis behavior) of steel pedestals (B-4) (NCS P1-1, 1-2)

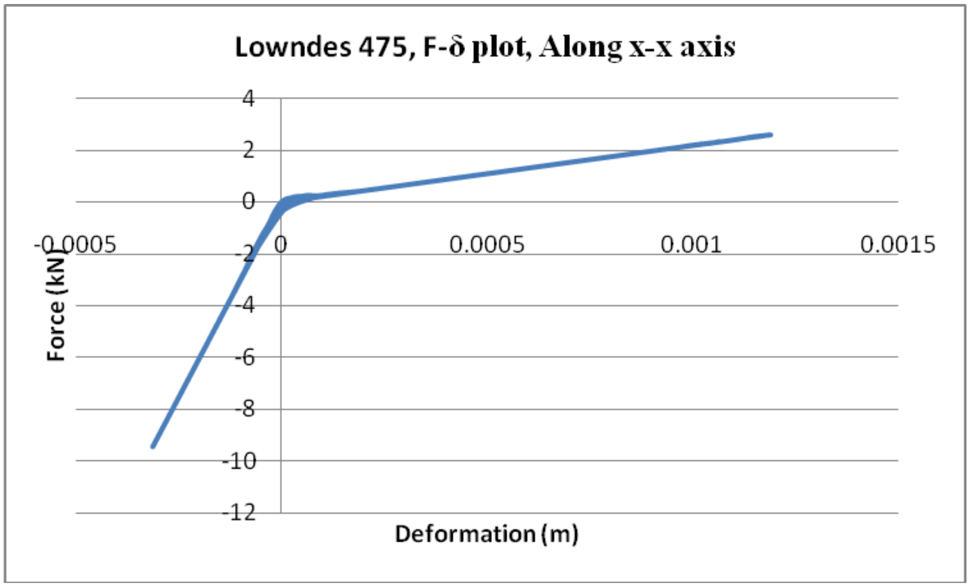


Figure 4-3: Force-deformation (hysteresis behavior) of steel pedestals (B-1) (NCS P2-1, 3-1)

Table 4-8: Maximum sliding of pedestals NCS P1-1, 1-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	1.55	0.8	2.03	1.02	2.1	1.15	147.78	214.29
Lowndes475	Min	-1.83	-1.3	-2.09	-1.91	-2.16	-2.03	143.54	208.33
Lowndes2475	Max	2.41	1.16	3.07	1.66	3.22	1.85	97.72	139.75
Lowndes2475	Min	-2.33	-1.97	-2.84	-2.74	-3.37	-3.1	105.63	133.53
Liberty475	Max	2.38	1.12	3.01	1.59	2.93	1.68	99.67	153.58
Liberty475	Min	-2.56	-2.17	-3.02	-2.93	-3.32	-3.24	99.34	135.54
Bartow475	Max	3.22	1.4	4.15	2.39	4.33	3.1	72.29	103.93
Bartow475	Min	-3.67	-2.11	-3.96	-3.49	-4.09	-3.81	75.76	110.02
Fortpayne475	Max	2.02	0.91	2.46	1.17	2.48	1.19	121.95	181.45
Fortpayne475	Min	-1.64	-0.89	-1.9	-1.44	-2.13	-1.49	157.89	211.27
Bartow2475	Max	5.41	3.62	5.69	4.21	5.8	3.85	52.72	77.59
Bartow2475	Min	-6.72	-4.35	-6.53	-4.15	-5.05	-4.66	44.64	89.11
Charleston475	Max	7.77	5.44	7.46	5.05	7.77	5.44	38.61	57.92
Charleston475	Min	-8.09	-5.21	-9.91	-5.48	-10.11	-5.72	30.27	44.51
Moderate Intensity Earthquakes									
Liberty2475	Max	12.9	10.28	18.63	12.35	22.69	14.24	16.10	19.83
Liberty2475	Min	-22.06	-10.68	-27.68	-12.01	-27.92	-13.58	10.84	16.12
El Centro	Max	11.26	6.94	15	9.68	16.57	11.44	20.00	27.16
El Centro	Min	-20.36	-6.93	-25.04	-9.07	-23.41	-8.84	11.98	19.22
Fortpayne2475	Max	5.15	3.1	6.1	3.58	5.91	3.5	49.18	76.14
Fortpayne2475	Min	-4.58	-2.91	-5.37	-3.67	-6.11	-4.24	55.87	73.65
High Intensity Earthquakes									
Northridge	Max	33.23	14.74	43.8	18.54	42.93	18.29	6.85	10.48
Northridge	Min	-61.33	-15.24	-70.2	-19.22	-59.28	-21.49	4.27	7.59
Charleston2475	Max	37.82	49.2	53.48	71.28	59.72	74.8	5.61	7.54
Charleston2475	Min	-103.34	-36.31	-142.87	-46.14	-122.06	-48.18	2.10	3.69

Table 4-9: Maximum sliding of pedestals NCS P2-1, 3-1

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	3.6	0.86	4.98	1	4.37	1.02	60.24	102.97
Lowndes475	Min	-0.99	-0.57	-1.82	-0.84	-2.49	-1.03	164.84	180.72
Lowndes2475	Max	4.99	1.5	4.36	1.75	3.96	1.61	60.12	113.64
Lowndes2475	Min	-1.14	-1.45	-1.5	-1.96	-2.72	-2.01	200.00	165.44
Liberty475	Max	5.06	0.83	4.65	1.19	3.94	1.29	59.29	114.21
Liberty475	Min	-2.05	-1.3	-1.84	-1.98	-2.53	-2.06	146.34	177.87
Bartow475	Max	5.77	1.82	7.27	2.13	6.41	1.95	41.27	70.20
Bartow475	Min	-3.81	-2.23	-4.18	-2.75	-4.3	-2.74	71.77	104.65
Fortpayne475	Max	4.39	1.1	5.02	1.18	3.83	1.16	59.76	117.49
Fortpayne475	Min	-0.74	-0.95	-1.53	-1.15	-2.73	-1.52	196.08	164.84
Bartow2475	Max	5.91	2.43	6.26	2.28	5.84	2.56	47.92	77.05
Bartow2475	Min	-2.66	-3.56	-3.13	-3.13	-3.87	-2.5	95.85	116.28
Charleston475	Max	7.91	3.21	10.43	5.19	12.54	6.48	28.76	35.89
Charleston475	Min	-7.07	-5.23	-9.59	-6.22	-11.42	-6.18	31.28	39.40
Moderate Intensity Earthquakes									
Liberty2475	Max	14.71	8.24	20.5	9.76	23.23	11.44	14.63	19.37
Liberty2475	Min	-16.15	-10.57	-22.64	-14.39	-23.85	-15.03	13.25	18.87
El Centro	Max	11.69	5.59	17.5	8.03	19.54	9.07	17.14	23.03
El Centro	Min	-11.95	-6.31	-17.39	-7.71	-18.74	-8.1	17.25	24.01
Fortpayne2475	Max	6.41	2.12	7.74	2.91	8.16	3.41	38.76	55.15
Fortpayne2475	Min	-4.56	-3.41	-5.49	-4.05	-5.71	-4.04	54.64	78.81
High Intensity Earthquakes									
Northridge	Max	36.59	8.47	52.85	9.7	55.15	9.72	5.68	8.16
Northridge	Min	-60.68	-22.86	-85.76	-28.83	-85.96	-29.96	3.50	5.23
Charleston2475	Max	85.37	45.66	116.2	59.9	127.18	65.35	2.58	3.54
Charleston2475	Min	-100.75	-54.93	-139.1	-74.66	-137.72	-77.66	2.16	3.27

Table 4-10: Maximum sliding of pedestals NCS P2-2, 3-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. ‘C/D’ ratio	
		X	Y	X	Y	X	Y	Bent ‘a’	Bent ‘b’
Low Intensity Earthquakes									
Lowndes475	Max	3.52	0.83	4.16	0.79	3.63	0.67	72.12	123.97
Lowndes475	Min	-0.82	-0.24	-0.96	-0.25	-2.03	-0.48	312.50	221.67
Lowndes2475	Max	4.52	0.92	4.31	0.88	3.14	0.47	66.37	143.31
Lowndes2475	Min	-0.96	-0.38	-1.2	-0.41	-2.06	-0.57	250.00	218.45
Liberty475	Max	3.6	0.69	3.99	0.63	2.97	0.41	75.19	151.52
Liberty475	Min	-1.15	-0.4	-1.45	-0.43	-1.81	-0.51	206.90	248.62
Bartow475	Max	6.16	1.31	6.93	1.26	6.3	1.13	43.29	71.43
Bartow475	Min	-2.44	-0.84	-3.08	-0.9	-3.73	-1.16	97.40	120.64
Fortpayne475	Max	3.94	0.68	4.16	0.63	2.98	0.45	72.12	151.01
Fortpayne475	Min	-0.81	-0.45	-1.32	-0.47	-2.05	-0.62	227.27	219.51
Bartow2475	Max	5.16	1.26	5.59	1.34	5.12	1.38	53.67	87.89
Bartow2475	Min	-2.53	-1.24	-2.89	-1.3	-3.17	-1.33	103.81	141.96
Charleston475	Max	10.35	3.05	12.22	3.13	12.23	3.38	24.55	36.79
Charleston475	Min	-7.02	-2.68	-8.55	-2.85	-9.9	-3.29	35.09	45.45
Moderate Intensity Earthquakes									
Liberty2475	Max	17.85	6.39	20.75	6.67	22.63	7.43	14.46	19.89
Liberty2475	Min	-14.54	-6.55	-18.17	-7.1	-20.86	-7.72	16.51	21.57
El Centro	Max	14.57	4.52	18.38	5.19	20.1	5.48	16.32	22.39
El Centro	Min	-11.94	-3.36	-14.53	-3.37	-15.99	-3.68	20.65	28.14
Fortpayne2475	Max	6.84	1.67	7.81	1.7	6.84	1.67	38.41	65.79
Fortpayne2475	Min	-2.52	-1.33	-3.21	-1.35	-4.62	-1.52	93.46	97.40
High Intensity Earthquakes									
Northridge	Max	36.01	9.02	43.24	8.84	46.17	9.55	6.94	9.75
Northridge	Min	-58.3	-18.91	-70.42	-18.56	-70.79	-17.89	4.26	6.36
Charleston2475	Max	81.93	63.48	96.92	69.8	105.7	67.33	3.10	4.26
Charleston2475	Min	-96.44	-49.13	-118.44	-51.42	-112.17	-49.37	2.53	4.01

4.2.4. Pounding analysis of the superstructure

The ‘C/D’ ratio in the pounding analysis indicates for which cases the value of the gap (25 mm) of the deck gap element is being exceeded. Pounding depends also on the duration of the impact force, but in this study the duration of impact is assumed to be same. When a larger force is transmitted to the superstructure, more damage can be expected. Based on the analysis results, Tables 4-11-4-13, the effect of pounding is severe for high intensity earthquakes and is also observed for moderate earthquakes El Centro and Liberty2475 and low intensity earthquakes Charleston475. However, the force transmitted to the superstructure due to pounding in the cases of low and moderate intensity earthquakes is relatively small and is expected not to cause any significant damage to superstructure. In other cases, the gap of the deck gap element is not exceeded and no force is transferred to the superstructure to cause pounding.

Table 4-11: Pounding analysis of superstructure NCS P1-1, 1-2

Ground Motion	Abutment (mm)	Deck joint (mm)	Axial(kN) (at abutment)	Axial(kN) (at joint)	Max. 'C/D' ratio	
					Abutment	Deck Joint
Low Intensity Earthquakes						
Lowndes475	1.64	3.46	0	0	15.49	7.34
Lowndes2475	3.25	7.18	0	0	7.82	3.54
Liberty475	3.33	6.68	0	0	7.63	3.80
Bartow475	4.58	10.72	0	0	5.55	2.37
Fortpayne475	2.63	5	0	0	9.66	5.08
Bartow2475	13.91	12.17	0	0	1.83	2.09
Charleston475	12.57	37.52	0	2.42	2.02	**0.68**
Moderate Intensity Earthquakes						
Liberty2475	39.4	72.16	2.8	9.35	**0.64**	**0.35**
El Centro	40.22	62.11	2.96	7.34	**0.63**	**0.41**
Fortpayne2475	8.41	16.27	0	0	3.02	1.56
High Intensity Earthquakes						
Northridge	154.24	193.32	25.77	33.59	**0.16**	**0.13**
Charleston2475	196.64	639.8	34.25	122.88	**0.13**	**0.04**

Table 4-12: Pounding analysis of superstructure NCS P2-1, 3-1

Ground Motion	Abutment (mm)	Deck joint (mm)	Axial(kN) (at abutment)	Axial(kN) (at joint)	Max. 'C/D' ratio	
					Abutment	Deck Joint
Low Intensity Earthquakes						
Lowndes475	0.78	7.56	0	0	32.56	3.36
Lowndes2475	2.94	12.31	0	0	8.64	2.06
Liberty475	5.25	13.08	0	0	4.84	1.94
Bartow475	7.85	17.71	0	0	3.24	1.43
Fortpayne475	0.92	11.42	0	0	27.61	2.22
Bartow2475	8.28	17.28	0	0	3.07	1.47
Charleston475	12.6	32.05	0	1.33	2.02	**0.79**
Moderate Intensity Earthquakes						
Liberty2475	15.44	38.48	0	2.62	1.65	**0.66**
El Centro	18.18	39.71	0	2.86	1.40	**0.64**
Fortpayne2475	8.29	15.61	0	0	3.06	1.63
High Intensity Earthquakes						
Northridge	63.97	150.27	7.71	24.97	**0.40**	**0.17**
Charleston2475	118.69	230.71	18.66	41.06	**0.21**	**0.11**

Table 4-13: Pounding analysis of superstructure NCS P2-2, 3-2

Ground Motion	Abutment (mm)	Deck joint (mm)	Axial(kN) (at abutment)	Axial(kN) (at joint)	Max. 'C/D' ratio	
					Abutment	Deck Joint
Low Intensity Earthquakes						
Lowndes475	0.82	7.42	0	0	30.98	3.42
Lowndes2475	4.34	10.36	0	0	5.85	2.45
Liberty475	1.6	10.13	0	0	15.88	2.51
Bartow475	2.89	13.74	0	0	8.79	1.85
Fortpayne475	1.02	10.07	0	0	24.90	2.52
Bartow2475	3.49	15.2	0	0	7.28	1.67
Charleston475	7.08	22.84	0	0	3.59	1.11
Moderate Intensity Earthquakes						
Liberty2475	10.01	41.08	0	3.14	2.54	**0.62**
El Centro	13.22	35.97	0	2.12	1.92	**0.71**
Fortpayne2475	4.85	17.8	0	0	5.24	1.43
High Intensity Earthquakes						
Northridge	55.62	141.18	6.04	23.16	**0.46**	**0.18**
Charleston2475	94.59	253.49	13.84	45.62	**0.27**	**0.10**

4.3. SUMMARY OF RESULTS

Based on the analysis results for the baseline models, it can be inferred that the usage of steel pedestals should be prohibited for bridges in regions of high seismicity. They can be used safely in low seismic zones, but for moderate seismic zone it should be accompanied by adequate retrofit measures like the inclusion of cable restrainers or other devices. The application of cable restrainers to this bridge model is described in Section 5.4.

5. PARAMETRIC STUDIES TO ASSESS THE CRITICAL PARAMETERS

5.1. EFFECT OF VARYING MASS ON STRUCTURAL RESPONSE

The mass of the superstructure is an important factor for determining the seismic response of the bridge. Given more mass, more inertial force will exist to resist a ground motion. Consequently, more components can be damaged, especially in the case of out of phase oscillation of the deck spans at the expansion joints. Lightweight concrete reduces the mass of the superstructure by 20%. If its high strength property is utilized then it can be even economical than the steel and concrete materials. The Benicia-Martinez Bridge located in California is designed to remain in service for an earthquake intensity measuring 7.3 on the Richter scale, which is the area's maximum recorded earthquake. This bridge was designed with lightweight concrete to optimize the benefits of this material and its effect on the structural performance. In the normal-weight concrete slab (NCS) bridge models i.e. the baseline models and normal-weight concrete slabs supported on steel girders are used.

In this study, two different variations of deck sections are used in the baseline models and these properties are summarized in Table 5-1. The lightweight concrete slab (LCS) bridge models consist of lightweight concrete slabs supported on steel girders and the normal-weight concrete deck and girder (NCDG) bridge models consist of normal-weight concrete slab and concrete girders, making the superstructure heavier. The aim of using a heavier superstructure is to examine the magnitude by which the induced seismic forces are incremented. Thus, the effect of variation of mass to the seismic behavior of the bridges is obtained by analyzing these models.

Table 5-1: Properties of various forms of decks

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 (lightweight 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)

5.1.1. Modal characteristics of the bridge

The time periods of first four modes of vibration for the LCS and NCDG models are shown in Table 5-2 and Table 5-3 respectively. The fundamental modes of vibration are same as the corresponding cases of the baseline models but the structural period has changed drastically.

As expected the structural period is lesser for LCS models due to reduction in the mass of the superstructure. The structural period for NCDG models is much higher than LCS or NCS models due to large increment in mass of the superstructure. The difference in mass of superstructure is relatively less between NCS and LCS models when compared to NCS and NCDG models because in LCS models only the deck is replaced with lightweight concrete but for NCDG models the girders are replaced using normal weight concrete thus increasing the mass substantially. The structural period thus is of less difference between NCS and LCS models, when compared to NCDG and NCS models.

Table 5-2: Structural period of first four modes (LCS models)

Mode	Time Period (s)		
	LCS P1-1, 1-2	LCS P2-1, 3-1	LCS P2-2, 3-2
1	0.77	0.68	0.78
2	0.69	0.64	0.61
3	0.37	0.35	0.43
4	0.36	0.34	0.41

Table 5-3: Structural period of first four modes (NCDG models)

Mode	Time Period (s)		
	NCDG P1-1, 1-2	NCDG P2-1, 3-1	NCDG P2-2, 3-2
1	1.55	1.35	1.57
2	1.37	1.28	1.22
3	0.84	0.78	0.98
4	0.71	0.67	0.82

5.1.2. Maximum displacement of pedestals

As indicated in Tables 5-4-5-6, the maximum displacement of the pedestals is exceeded for the high intensity earthquakes (Northridge and Charleston2475), and also for the moderate intensity earthquakes (Liberty2475 and El Centro). However, compared to the behavior of these pedestals for NCS models the 'C/D' ratios have shown a significant improvement. Thus, if retrofitted using cable restrainers it is expected to perform better than NCS models for moderate intensity earthquake zone. However, for high intensity earthquake zones, even LCS models are not expected to perform well even if retrofitted.

According to Tables 5-7-5-9, the maximum displacement of the pedestals is exceeded for the high intensity earthquakes (Northridge and Charleston2475), and also for the moderate intensity earthquakes (Liberty2475 and El Centro) and even Charleston475, which is a low intensity earthquake. When compared to the results of NCS models the 'C/D' ratios have shown a significant decrease. Thus, a heavier superstructure is not recommended for high and moderate intensity earthquakes. Even for low intensity earthquakes, they need to be checked whether they require retrofitting or not.

Table 5-4: Maximum displacement of pedestals LCS P1-1, 1-2

Ground Motion	**Type**	**BTJ-2a**		**BTJ-2b**		**BTJ-4**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	3.06	2.88	10.29	5.14	10.31	6.02	4.31	13.71
Lowndes475	Min	-1.82	-6.81	-6.58	-8.85	-6.76	-10.95	6.58	7.54
Lowndes2475	Max	4.07	2.49	10.84	5.41	11.07	6.33	4.02	13.04
Lowndes2475	Min	-2.59	-5.93	-6.28	-9.98	-6.44	-11.91	6.90	6.93
Liberty475	Max	3.06	2.88	10.29	5.14	10.31	6.02	4.31	13.71
Liberty475	Min	-1.82	-6.81	-6.58	-8.85	-6.76	-10.95	6.58	7.54
Bartow475	Max	4.66	4.15	10.41	8.29	10.41	10.83	4.27	7.62
Bartow475	Min	-3.55	-9.1	-7.55	-15.54	-7.83	-18.83	5.68	4.38
Fortpayne475	Max	2.43	1.56	7.09	4.53	7.08	5.68	6.27	14.53
Fortpayne475	Min	-2.14	-3.74	-4.64	-8.41	-4.65	-9.34	9.56	8.84
Bartow2475	Max	11.57	8.23	11.72	8.96	12.12	10.67	3.67	7.74
Bartow2475	Min	-8.38	-19.66	-12.79	-19.49	-13.17	-22.34	3.38	3.70
Charleston475	Max	15.15	10.7	22.84	24.97	23.49	30.85	1.89	2.68
Charleston475	Min	-10.53	-18.18	-40.82	-24.7	-40.76	-28.51	1.09	2.90
Moderate Intensity Earthquakes									
Liberty2475	Max	12.19	21.41	66.77	53.78	67.54	64.93	**0.66**	1.27
Liberty2475	Min	-26.46	-23.48	-87.77	-43.45	-87.78	-45.44	**0.51**	1.82
El Centro	Max	23.03	19.1	48.19	46.88	48.37	57.6	**0.92**	1.43
El Centro	Min	-30.79	-21.91	-75.64	-30.02	-74.7	-36.93	**0.59**	2.24
Fortpayne2475	Max	8.86	5.92	19.32	12.48	19.78	17.14	2.25	4.82
Fortpayne2475	Min	-8.05	-14.98	-23.26	-19.72	-23.19	-21.05	1.91	3.92
High Intensity Earthquakes									
Northridge	Max	33.7	39.78	117.62	68.24	116.89	81.69	**0.38**	1.01
Northridge	Min	-114.79	-47.6	-216.48	-64.89	-216.17	-71.52	**0.21**	1.15
Charleston2475	Max	25.42	98.49	225.79	246.39	223.99	292.12	**0.20**	**0.28**
Charleston2475	Min	-162.07	-60.19	-687.39	-119.24	-679.06	-133.7	**0.06**	**0.62**

Table 5-5: Maximum displacement of pedestals LCS P2-1, 3-1

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	11.8	2.36	12.45	4.46	12.24	5.35	2.86	9.50
Lowndes475	Min	-1.76	-1.63	-3.21	-8.23	-3.42	-9.58	10.40	5.30
Lowndes2475	Max	11.85	2.32	11.93	6.59	11.68	7.99	2.98	6.36
Lowndes2475	Min	-1.36	-1.85	-2.47	-6.69	-2.56	-8.46	13.89	6.00
Liberty475	Max	11.8	2.36	12.45	4.46	12.24	5.35	2.86	9.50
Liberty475	Min	-1.76	-1.63	-3.21	-8.23	-3.42	-9.58	10.40	5.30
Bartow475	Max	13.24	2.3	18.57	5.93	18.39	6.89	1.91	7.37
Bartow475	Min	-5.64	-2.9	-10.3	-9.26	-10.39	-11.04	3.42	4.60
Fortpayne475	Max	6.62	2.07	11.14	4.27	11.02	4.77	3.19	10.65
Fortpayne475	Min	-0.76	-0.73	-3.05	-2.84	-3.11	-4.03	11.43	12.61
Bartow2475	Max	16.57	6.33	18.52	9.1	18.24	11.75	1.92	4.32
Bartow2475	Min	-9.7	-11.31	-10.8	-10.15	-10.79	-13.22	3.29	3.84
Charleston475	Max	15.92	8.01	32.25	18.4	32.4	21.24	1.10	2.39
Charleston475	Min	-9.61	-11.65	-21.68	-18.56	-21.95	-22.28	1.62	2.28
Moderate Intensity Earthquakes									
Liberty2475	Max	17.29	13.96	60.81	34.01	61.41	40.87	**0.58**	1.24
Liberty2475	Min	-12.66	-13.66	-44.62	-37.46	-44.94	-42.4	**0.79**	1.20
El Centro	Max	14.76	11.01	56.14	22.33	55.13	25.58	**0.63**	1.99
El Centro	Min	-14.91	-14.23	-38.8	-29.18	-38.43	-35.03	**0.92**	1.45
Fortpayne2475	Max	17.81	5.04	21.09	8.9	20.98	12.79	1.69	3.97
Fortpayne2475	Min	-7.37	-10.74	-13.76	-11.26	-13.72	-13.56	2.58	3.75
High Intensity Earthquakes									
Northridge	Max	31.91	20.4	99.09	34.95	98.46	41.93	**0.36**	1.21
Northridge	Min	-50.36	-29.69	-145.73	-71.53	-142.37	-86.17	**0.24**	**0.59**
Charleston2475	Max	61.11	75.25	164.98	171.19	171.05	212.41	**0.21**	**0.24**
Charleston2475	Min	-74.44	-64.09	-249.96	-167.49	-251.51	-197.06	**0.14**	**0.26**

Table 5-6: Maximum displacement of pedestals LCS P2-2, 3-2

Ground Motion	**Type**	**BTJ-2a**		**BTJ-2b**		**BTJ-4**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	11.74	0.55	11.72	0.71	11.48	1.18	7.57	43.05
Lowndes475	Min	-2.73	-0.27	-2.51	-1.34	-2.58	-2.13	32.56	23.85
Lowndes2475	Max	12.62	1	12.77	1.65	12.36	1.83	6.96	27.76
Lowndes2475	Min	-4.68	-0.34	-3.25	-1.8	-3.41	-2.46	18.99	20.65
Liberty475	Max	11.74	0.55	11.72	0.71	11.48	1.18	7.57	43.05
Liberty475	Min	-2.73	-0.27	-2.51	-1.34	-2.58	-2.13	32.56	23.85
Bartow475	Max	11.45	1.11	17.67	0.76	17.34	1.24	5.03	40.97
Bartow475	Min	-2.53	-0.79	-6.15	-3.82	-6.32	-4.77	14.06	10.65
Fortpayne475	Max	8.09	0.68	9.71	0.86	9.46	1.11	9.15	45.77
Fortpayne475	Min	-0.73	-0.6	-2.15	-1.71	-2.22	-2.52	40.04	20.16
Bartow2475	Max	14.2	1.52	20.2	5.37	20.15	6.83	4.40	7.44
Bartow2475	Min	-5.83	-1.68	-8.31	-6.27	-8.3	-8	10.70	6.35
Charleston475	Max	16.13	2.46	32.43	10.1	32.55	11.51	2.73	4.41
Charleston475	Min	-6.28	-2.84	-18.42	-10.18	-18.88	-12.74	4.71	3.99
Moderate Intensity Earthquakes									
Liberty2475	Max	23.57	6.53	54.74	36.73	55.06	42.38	1.61	1.20
Liberty2475	Min	-7.06	-6.66	-37.32	-34.49	-37.83	-40.77	2.35	1.25
El Centro	Max	24.18	3.6	56.52	31.16	55.81	36.34	1.57	1.40
El Centro	Min	-10.25	-4.84	-31.41	-23.26	-31.36	-28.65	2.83	1.77
Fortpayne2475	Max	18.44	1.2	19.7	6.6	19.57	6.93	4.51	7.33
Fortpayne2475	Min	-6.06	-4.79	-10.09	-5.53	-10.44	-6.99	8.51	7.27
High Intensity Earthquakes									
Northridge	Max	28.41	8.89	84.01	45.27	84.03	53.03	1.06	**0.96**
Northridge	Min	-44.98	-28.07	-126.13	-84.41	-125.61	-92.45	**0.70**	**0.55**
Charleston2475	Max	58.28	130.23	166.09	378.9	168.97	433.83	**0.53**	**0.12**
Charleston2475	Min	-61.66	-96.48	-221.41	-226.23	-219.5	-258.75	**0.40**	**0.20**

Table 5-7: Maximum displacement of pedestals NCDG P1-1, 1-2

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	4.76	3.82	16.75	8.33	16.79	9.03	2.65	9.14
Lowndes475	Min	-3.27	-6.31	-12.76	-17.31	-12.86	-18.46	3.46	4.47
Lowndes2475	Max	9.7	6.47	15.66	7.67	15.68	8.08	2.83	10.22
Lowndes2475	Min	-4.62	-13.1	-8.88	-15.73	-8.96	-16.7	4.96	4.94
Liberty475	Max	10.53	6.59	11.06	7.39	11.1	7.93	4.00	10.41
Liberty475	Min	-6.65	-11.97	-8.01	-14.09	-8.1	-15.16	5.49	5.45
Bartow475	Max	9.5	10.19	22.49	23.18	22.73	24.61	1.96	3.35
Bartow475	Min	-9.85	-17.54	-44.18	-22.41	-44.26	-23.93	1.00	3.45
Fortpayne475	Max	6.27	2.86	9.71	5.71	9.74	6.04	4.56	13.67
Fortpayne475	Min	-4.1	-6.36	-5.38	-11.6	-5.45	-12.38	8.16	6.67
Bartow2475	Max	10.56	12.15	19.79	21.89	19.9	23.11	2.23	3.57
Bartow2475	Min	-10.62	-17.62	-20.66	-22.68	-20.72	-23.67	2.15	3.49
Charleston475	Max	14.79	29.81	22.51	46.69	22.78	49.25	1.95	1.68
Charleston475	Min	-34.01	-32.72	-64.47	-43.29	-64.48	-44.93	**0.69**	1.84
Moderate Intensity Earthquakes									
Liberty2475	Max	44.53	56.31	132.72	113.08	133.26	120.93	**0.33**	**0.68**
Liberty2475	Min	-75.58	-35.15	-178.84	-70.73	-179.22	-73.49	**0.25**	1.12
El Centro	Max	31.87	55.93	73.92	77.02	73.65	81.12	**0.60**	1.02
El Centro	Min	-69.35	-34.05	-99.24	-33.43	-99.01	-35.23	**0.45**	2.34
Fortpayne2475	Max	16.75	12.43	28.08	30.97	28.16	32.15	1.58	2.57
Fortpayne2475	Min	-20.52	-16.47	-40.93	-28.24	-40.96	-29.41	1.09	2.81
High Intensity Earthquakes									
Northridge	Max	132.47	59.51	303.7	167.76	303.61	180.02	**0.15**	**0.46**
Northridge	Min	-190.64	-62.82	-549.16	-90.64	-548.01	-96.59	**0.08**	**0.85**
Charleston2475	Max	148.95	297.6	485.72	853.81	486.1	900.89	**0.09**	**0.09**
Charleston2475	Min	-642.7	-116.19	-1217.59	-308.97	-1209.23	-320.54	**0.04**	**0.26**

Table 5-8: Maximum displacement of pedestals NCDG P2-1, 3-1

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	14.49	3.08	13.53	5.09	13.48	5.34	2.45	9.51
Lowndes475	Min	-5.71	-3.08	-2.36	-9.33	-2.37	-10.02	6.23	5.07
Lowndes2475	Max	15.38	6.72	12.49	4.72	12.44	4.89	2.31	7.56
Lowndes2475	Min	-9.17	-6.68	-3.33	-8.37	-3.37	-9	3.88	5.64
Liberty475	Max	11.78	3.98	15.4	6.46	15.37	6.61	2.31	7.69
Liberty475	Min	-3.6	-9.1	-7.11	-11.14	-7.17	-11.76	4.96	4.32
Bartow475	Max	19.26	6.08	29.7	16.09	29.77	17.02	1.19	2.98
Bartow475	Min	-10.17	-11.57	-20.13	-14.56	-20.18	-15.1	1.76	3.36
Fortpayne475	Max	11.69	4.05	16.64	4.68	16.64	4.78	2.14	10.63
Fortpayne475	Min	-2.34	-3.7	-9.63	-6.7	-9.68	-6.9	3.67	7.36
Bartow2475	Max	17.09	9.08	20.92	13.22	20.97	13.71	1.70	3.71
Bartow2475	Min	-9.19	-12.25	-21.93	-13.97	-22.02	-15.14	1.61	3.36
Charleston475	Max	17.54	17.66	33.26	16.17	33.31	16.86	1.07	2.88
Charleston475	Min	-17.89	-21.15	-34.79	-33.49	-35.07	-35.56	1.01	1.43
Moderate Intensity Earthquakes									
Liberty2475	Max	43.69	32.36	73.61	57.89	74.22	61.9	**0.48**	**0.82**
Liberty2475	Min	-36.94	-43.75	-96.51	-83.38	-96.7	-87.27	**0.37**	**0.58**
El Centro	Max	41.49	24.39	58.77	44.86	58.82	48.19	**0.60**	1.05
El Centro	Min	-27.48	-30.24	-61.68	-52.68	-61.41	-54.78	**0.58**	**0.93**
Fortpayne2475	Max	21.61	10.07	30.74	21.42	30.95	21.88	1.15	2.32
Fortpayne2475	Min	-12.72	-12.42	-22.8	-20.77	-22.83	-21.48	1.56	2.36
High Intensity Earthquakes									
Northridge	Max	87.54	39.46	218.52	84.59	220.39	91.36	**0.16**	**0.56**
Northridge	Min	-155.22	-85.54	-418.66	-157.06	-419.83	-166.3	**0.08**	**0.31**
Charleston2475	Max	192.4	149.39	376.3	450.14	383.3	490.11	**0.09**	**0.10**
Charleston2475	Min	-338.55	-239.21	-771.46	-543.04	-773.55	-575.41	**0.05**	**0.09**

Table 5-9: Maximum displacement of pedestals NCDG P2-2, 3-2

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	12.66	0.9	13.16	1.88	13.1	1.98	6.75	25.66
Lowndes475	Min	-2.74	-0.47	-3.05	-1.69	-3.09	-1.76	28.77	28.86
Lowndes2475	Max	11.12	0.79	11.8	2	11.78	2.38	7.53	21.34
Lowndes2475	Min	-2.21	-2.59	-3.98	-4.89	-3.98	-5.44	22.33	9.34
Liberty475	Max	11.24	1.03	12.83	2.69	12.82	3.03	6.93	16.77
Liberty475	Min	-2.49	-3.51	-4.81	-5.28	-4.84	-5.5	18.37	9.24
Bartow475	Max	16.59	1.09	28.44	9.23	28.46	9.33	3.12	5.44
Bartow475	Min	-4.97	-5.5	-17.87	-11.51	-18.03	-12.03	4.93	4.22
Fortpayne475	Max	11.33	0.72	13.21	1.28	13.15	1.53	6.73	33.20
Fortpayne475	Min	-2.13	-3.08	-4.73	-4.11	-4.73	-4.48	18.79	11.34
Bartow2475	Max	17.35	6.19	23	15.36	23	15.99	3.86	3.18
Bartow2475	Min	-5.63	-7.39	-12.14	-11.94	-12.22	-12.28	7.27	4.14
Charleston475	Max	20.44	9.28	33.73	17.86	33.86	19.03	2.63	2.67
Charleston475	Min	-11.8	-10.66	-36.62	-31.35	-36.87	-32.96	2.41	1.54
Moderate Intensity Earthquakes									
Liberty2475	Max	35.98	37.98	62.59	83.63	62.97	86.66	1.41	**0.59**
Liberty2475	Min	-30.2	-38.01	-96.14	-85.42	-96.4	-87.8	**0.92**	**0.58**
El Centro	Max	40.39	37.97	53.36	72.83	53.46	76.02	1.66	**0.67**
El Centro	Min	-24.19	-25.12	-58.64	-39.93	-58.62	-41.44	1.52	1.23
Fortpayne2475	Max	20.22	4.4	34.09	15.89	34.1	16.87	2.61	3.01
Fortpayne2475	Min	-8.32	-7.26	-19.77	-18.1	-19.98	-18.61	4.45	2.73
High Intensity Earthquakes									
Northridge	Max	75.83	63.15	214.52	132.09	215.63	137.12	**0.41**	**0.37**
Northridge	Min	-135.43	-77.29	-381.15	-164.05	-381.22	-169.47	**0.23**	**0.30**
Charleston2475	Max	169.06	434.28	372.57	698.79	377.23	741.96	**0.24**	**0.07**
Charleston2475	Min	-297.34	-270.06	-681.67	-292.84	-682.16	-304.49	**0.13**	**0.17**

5.1.3. Maximum force transmitted to pedestals

According to Tables 5-10-5-12, the force transmitted to the pedestals has decreased substantially due to reduction of the weight of the superstructure when compared to the response of the NCS models. In fact for pedestal configuration P1-1, 1-2 and P2-2, 3-2 it is showing 'C/D' ratios greater than one for high intensity Northridge earthquake.

According to Tables 5-13-5-15, the force transmitted to the pedestals has relatively increased when compared with the NCS models. This can be expected because, as stated earlier, when we are increasing mass of the superstructure, the inertial force to resist the ground motion is much higher.

5.1.4. Maximum sliding of pedestals

The 'C/D' ratios are having safe values for all the cases as indicated in Tables 5-16-5-18. Similar to the NCS models, sliding seems to not be of much concern provided adequate seat width (W) is available.

The 'C/D' ratios for sliding of NCDG models are having relatively lower value than the NCS models as indicated in Tables 5-19-5-21. In fact for P2-1, 3-1 pedestal configuration, the 'C/D' ratios are less than one for Charleston2475 earthquake which means that the pedestals will slide in excess of the seat width. Even for other cases, the sliding values are close to one and hence sliding the seat width (W) should be increased for corresponding critical cases.

Table 5-10: Maximum force transmitted to pedestals LCS P1-1, 1-2

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	9.39	9.282	20.295	14.877	17.02	17.7	17.10	7.08
Lowndes475	Min	-4.44	-3.69	-11.5	-4.24	-12.59	-6.26	34.03	46.64
Lowndes2475	Max	9.07	8.495	20.038	15.606	18.89	19.75	17.32	6.35
Lowndes2475	Min	-4.58	-3.32	-12.63	-4.89	-14.86	-7.07	28.83	41.30
Liberty475	Max	9.39	9.282	20.295	14.877	17.02	17.7	17.10	7.08
Liberty475	Min	-4.44	-3.69	-11.5	-4.24	-12.59	-6.26	34.03	46.64
Bartow475	Max	8.55	11.245	21.599	23.229	23.29	24.54	14.90	5.11
Bartow475	Min	-5.72	-3.96	-12.29	-7.39	-14.29	-15.22	29.98	19.18
Fortpayne475	Max	7.53	4.687	13.528	12.878	12.28	18.88	25.66	6.64
Fortpayne475	Min	-3.22	-2.11	-8.35	-4.14	-10.06	-5.7	42.58	51.22
Bartow2475	Max	28.26	23.428	29.081	23.199	29.99	24.59	11.57	5.10
Bartow2475	Min	-16.93	-9.12	-16.65	-10.24	-21.96	-21.43	19.51	13.62
Charleston475	Max	28.29	24.361	39.498	30.635	41.34	37.05	8.40	3.38
Charleston475	Min	-19.63	-11.77	-37.67	-16.64	-41.93	-27.96	10.22	10.44
Moderate Intensity Earthquakes									
Liberty2475	Max	33.44	29.436	92.336	56.521	106.46	82.1	3.26	1.53
Liberty2475	Min	-26.7	-16.34	-90.31	-49.82	-95.05	-106.12	4.51	2.75
El Centro	Max	33.17	28.701	76.438	49.948	98.23	76.48	3.53	1.64
El Centro	Min	-22.47	-13.41	-72.08	-37.72	-90.09	-96.3	4.76	3.03
Fortpayne2475	Max	27.56	17.778	31.746	25.483	32.39	28.83	10.72	4.35
Fortpayne2475	Min	-10.28	-8.12	-23.29	-12.1	-29.33	-20.01	14.61	14.59
High Intensity Earthquakes									
Northridge	Max	97.55	48.936	113.458	74.616	113.46	102.38	3.06	1.22
Northridge	Min	-66.65	-56.03	-127.23	-144.27	-133.48	-247.5	3.21	1.18
Charleston2475	Max	113.46	84.179	113.573	257.831	113.55	362.27	3.06	**0.35**
Charleston2475	Min	-20.66	-96.6	-204.7	-458.83	-219.35	-531.68	1.95	**0.55**

Table 5-11: Maximum force transmitted to pedestals LCS P2-1, 3-1

Ground Motion	**Type**	**B-2a**		**B-2b**		**B-4**		**Max. 'C/D' ratio**	
		Shear (y-y)	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Y-Y**	**X-X**
Low Intensity Earthquakes									
Lowndes475	Max	8.86	4.18	11.07	11.95	10.46	14.58	21.28	11.22
Lowndes475	Min	-0.13	-11.16	-0.43	-17.38	-5.47	-19.56	37.37	6.95
Lowndes2475	Max	9.55	4.4	10.15	12.02	10.03	17.4	23.20	9.40
Lowndes2475	Min	-0.89	-11.55	-0.81	-16.08	-2.53	-18.69	80.80	7.28
Liberty475	Max	8.86	4.18	11.07	11.95	10.46	14.58	21.28	11.22
Liberty475	Min	-0.13	-11.16	-0.43	-17.38	-5.47	-19.56	37.37	6.95
Bartow475	Max	11.86	5.14	16.8	12.24	18.39	14.84	12.81	11.02
Bartow475	Min	-1.76	-13.22	-8.61	-18.03	-18.34	-21.67	11.15	6.28
Fortpayne475	Max	7.51	3.02	10.1	6.62	10.02	10.26	23.32	15.94
Fortpayne475	Min	-0.87	-10.57	-0.58	-12.66	-2.68	-13.81	76.28	9.85
Bartow2475	Max	16.31	15.63	18.2	16.68	28.53	21.04	8.26	7.77
Bartow2475	Min	-6.68	-19.97	-14.25	-18.38	-22.28	-27.87	9.18	4.88
Charleston475	Max	18.13	15.97	37.79	24.56	47.53	41.81	4.96	3.91
Charleston475	Min	-11.49	-20.79	-40.06	-27.2	-52.77	-39.85	3.87	3.41
Moderate Intensity Earthquakes									
Liberty2475	Max	29.24	19.25	83.38	58.16	97.22	77.79	2.42	2.10
Liberty2475	Min	-14.15	-21.65	-94.93	-58.79	-112.22	-77.12	1.82	1.76
El Centro	Max	33.14	18.23	78.13	58.13	90.18	78.79	2.61	2.08
El Centro	Min	-16.13	-20.64	-93.79	-53.41	-128.75	-75.36	1.59	1.80
Fortpayne2475	Max	15.3	14.27	21.57	16.69	26.16	24.8	9.00	6.59
Fortpayne2475	Min	-5.21	-19.64	-21.27	-19.27	-29.92	-26.47	6.83	5.14
High Intensity Earthquakes									
Northridge	Max	73.29	33.07	165	78.57	193.19	94.7	1.22	1.73
Northridge	Min	-41.97	-34.58	-191.34	-105.05	-215.39	-155.5	**0.95**	**0.87**
Charleston2475	Max	94.26	100.27	211.34	250.2	263.22	368.92	**0.89**	**0.44**
Charleston2475	Min	-89.08	-63.99	-308.56	-235.27	-382.11	-335.26	**0.53**	**0.41**

Table 5-12: Maximum force transmitted to pedestals LCS P2-2, 3-2

Ground Motion	**Type**	**B-2a**		**B-2b**		**B-4**		**Max. 'C/D' ratio**	
		Shear (y-y)	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Y-Y**	**X-X**
Low Intensity Earthquakes									
Lowndes475	Max	10.05	3.64	10.86	10.13	8.54	11.05	22.67	21.96
Lowndes475	Min	-0.53	-11.97	-1.06	-12.93	-5.2	-13.12	45.64	20.76
Lowndes2475	Max	15.07	4.33	11.08	11.9	10.1	12.44	16.34	19.50
Lowndes2475	Min	-2.28	-12.01	-1.77	-12.8	-7.63	-13.07	31.10	20.84
Liberty475	Max	10.05	3.64	10.86	10.13	8.54	11.05	22.67	21.96
Liberty475	Min	-0.53	-11.97	-1.06	-12.93	-5.2	-13.12	45.64	20.76
Bartow475	Max	9.57	6.46	17.27	11.42	19.96	12.16	12.33	19.95
Bartow475	Min	-0.52	-12.08	-7.51	-14.24	-14.84	-14.75	15.99	18.47
Fortpayne475	Max	6.42	8.18	8.79	10.85	7.87	10.89	28.01	22.28
Fortpayne475	Min	0	-12.23	-0.01	-13.28	-1.85	-13.31	128.28	20.47
Bartow2475	Max	13.63	11.02	22.84	15.47	32.48	16.81	7.58	14.43
Bartow2475	Min	-4.62	-12.68	-13.98	-17.39	-23.94	-20.83	9.91	13.08
Charleston475	Max	14.31	13.54	44.05	18.96	55.3	22.33	4.45	10.87
Charleston475	Min	-5.16	-12.73	-32.55	-20.77	-49.44	-23.86	4.80	11.42
Moderate Intensity Earthquakes									
Liberty2475	Max	34.13	14.88	88.59	35.49	93.61	37.6	2.63	6.45
Liberty2475	Min	-11.21	-13.62	-98.76	-37.24	-100.44	-43.74	2.36	6.23
El Centro	Max	28.79	13.76	86.57	34.34	91.85	36.8	2.68	6.59
El Centro	Min	-8.08	-14.04	-104.88	-34.19	-150.13	-37.07	1.58	7.35
Fortpayne2475	Max	21.24	11.3	26.93	16.94	34.66	18.94	7.10	12.81
Fortpayne2475	Min	-6.9	-14.79	-13.71	-16.73	-28.97	-18.61	8.19	14.64
High Intensity Earthquakes									
Northridge	Max	61.9	19.94	166.92	44.04	183.04	57.11	1.35	4.25
Northridge	Min	-25.12	-32.82	-188.2	-95.9	-194.03	-129.27	1.22	2.11
Charleston2475	Max	96.44	118.01	229.88	209.75	254.81	244.75	**0.97**	**0.99**
Charleston2475	Min	-69.24	-120.59	-435.5	-315.85	-385.3	-391.49	**0.54**	**0.70**

Table 5-13: Maximum force transmitted to pedestals NCDG P1-1, 1-2

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	29.06	23.68	10.75	12.19	28.89	24.15	11.94	5.19
Lowndes475	Min	-19.44	-9.14	-5.12	-3.64	-20.45	-14.67	20.95	19.90
Lowndes2475	Max	28.28	22.42	18.59	19.08	25.31	23.4	12.27	5.36
Lowndes2475	Min	-18.53	-8.19	-10.37	-6.41	-19.88	-12.14	21.55	24.05
Liberty475	Max	25.48	23.28	20.94	18.5	21.52	23.48	13.62	5.34
Liberty475	Min	-13.1	-7.09	-11.8	-5.7	-13.85	-9.36	30.93	31.19
Bartow475	Max	41.48	30.29	28.03	25.05	45.29	31.39	7.66	3.99
Bartow475	Min	-41.76	-15.97	-11.99	-9.62	-43.06	-22.68	9.95	12.87
Fortpayne475	Max	18	17.83	13.96	10.53	15.67	19.52	19.28	6.42
Fortpayne475	Min	-11.77	-5.75	-7.4	-3.27	-11.82	-7.16	36.24	40.78
Bartow2475	Max	31.12	29.76	28.54	24.91	31.53	30.29	11.01	4.14
Bartow2475	Min	-24.51	-15.35	-12.51	-8.67	-26.57	-22.43	16.12	13.02
Charleston475	Max	55.54	50.08	34.82	34.44	70.04	64.03	4.96	1.96
Charleston475	Min	-65.49	-54.13	-27.24	-23.56	-59.68	-95.16	6.54	3.07
Moderate Intensity Earthquakes									
Liberty2475	Max	113.46	119.97	57.05	62.35	113.46	149.84	3.06	0.84
Liberty2475	Min	-139.73	-216.26	-74.65	-48.36	-148.56	-237.39	2.88	1.23
El Centro	Max	113.46	88.98	61.36	60.01	113.46	107.02	3.06	1.17
El Centro	Min	-105.23	-110.14	-72.8	-49.46	-106.58	-111.01	4.02	2.63
Fortpayne2475	Max	38.58	33.41	30.87	24.38	42.72	37.64	8.12	3.33
Fortpayne2475	Min	-41.78	-21.59	-18.15	-8.28	-46.51	-31.6	9.21	9.24
High Intensity Earthquakes									
Northridge	Max	113.46	198.61	113.46	67.97	113.46	222.39	3.06	0.56
Northridge	Min	-242.51	-304.33	-114.36	-157.18	-279.47	-403.2	1.53	0.72
Charleston2475	Max	113.47	949.4	113.46	278.29	113.9	1134.37	3.05	**0.11**
Charleston2475	Min	-356.72	-1668.95	-141.4	-549.62	-405.01	-1628.44	1.06	**0.17**

Table 5-14: Maximum force transmitted to pedestals NCDG P2-1, 3-1

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	14.85	5.66	10.61	11.4	9.66	13.96	15.86	11.71
Lowndes475	Min	-1.25	-12.57	-0.18	-19.09	-4.54	-20.51	45.03	6.63
Lowndes2475	Max	17.16	12.26	11.26	12.63	11.02	13.65	13.73	11.98
Lowndes2475	Min	-5.44	-16.83	-0.15	-17.77	-3.38	-19.61	37.58	6.94
Liberty475	Max	10.8	12.06	13.43	12.74	14.29	15.08	16.48	10.84
Liberty475	Min	-0.32	-18.15	-3.32	-20.1	-11.91	-22.73	17.16	5.98
Bartow475	Max	18.23	12.3	33.41	23.5	39.97	26.69	5.89	6.13
Bartow475	Min	-5.77	-18.7	-35.42	-21.86	-40.3	-26.48	5.07	5.14
Fortpayne475	Max	11.13	6.64	17.25	8.14	17.6	11.06	13.38	14.79
Fortpayne475	Min	-0.19	-13.72	-7.24	-15.83	-14.61	-16.55	13.99	8.22
Bartow2475	Max	15.88	16.34	36.62	21.07	45.14	22.38	5.22	7.31
Bartow2475	Min	-5.26	-20.99	-24.85	-22.2	-31.4	-28.9	6.51	4.71
Charleston475	Max	24.99	24.79	73.11	48.37	78.76	61.02	2.99	2.68
Charleston475	Min	-26	-28	-54.07	-57.11	-55.45	-65.61	3.69	2.07
Moderate Intensity Earthquakes									
Liberty2475	Max	33.79	52.3	119.84	98.59	138.46	113.44	1.70	1.44
Liberty2475	Min	-36.32	-63.33	-135.4	-127.43	-146.64	-156.96	1.39	0.87
El Centro	Max	49.69	63.51	104.46	86.91	115.86	99.52	2.03	1.64
El Centro	Min	-77.94	-53.44	-101.39	-87.23	-129.49	-103.1	1.58	1.32
Fortpayne2475	Max	21.97	16.91	41.55	29.38	49.88	40.3	4.72	4.06
Fortpayne2475	Min	-6.35	-20.77	-42.83	-30.05	-62.41	-37.89	3.28	3.59
High Intensity Earthquakes									
Northridge	Max	122.84	77.88	318.89	173.83	438.16	171.52	**0.54**	**0.94**
Northridge	Min	-69.85	-106.73	-544.49	-222.05	-563.36	-304.75	**0.36**	**0.45**
Charleston2475	Max	195.74	273.72	528.59	694.29	747.83	888.53	**0.31**	**0.18**
Charleston2475	Min	-435.29	-275.92	-955.89	-779.62	-1048.14	-994.56	**0.20**	**0.14**

Table 5-15: Maximum force transmitted to pedestals NCDG P2-2, 3-2

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	12.66	0.9	13.16	1.88	13.1	1.98	18.71	122.55
Lowndes475	Min	-2.74	-0.47	-3.05	-1.69	-3.09	-1.76	76.80	154.78
Lowndes2475	Max	11.12	0.79	11.8	2	11.78	2.38	20.86	101.95
Lowndes2475	Min	-2.21	-2.59	-3.98	-4.89	-3.98	-5.44	59.63	50.08
Liberty475	Max	11.24	1.03	12.83	2.69	12.82	3.03	19.19	80.08
Liberty475	Min	-2.49	-3.51	-4.81	-5.28	-4.84	-5.5	49.03	49.53
Bartow475	Max	16.59	1.09	28.44	9.23	28.46	9.33	8.65	26.01
Bartow475	Min	-4.97	-5.5	-17.87	-11.51	-18.03	-12.03	13.16	22.65
Fortpayne475	Max	11.33	0.72	13.21	1.28	13.15	1.53	18.64	158.59
Fortpayne475	Min	-2.13	-3.08	-4.73	-4.11	-4.73	-4.48	50.17	60.81
Bartow2475	Max	17.35	6.19	23	15.36	23	15.99	10.70	15.17
Bartow2475	Min	-5.63	-7.39	-12.14	-11.94	-12.22	-12.28	19.42	22.18
Charleston475	Max	20.44	9.28	33.73	17.86	33.86	19.03	7.27	12.75
Charleston475	Min	-11.8	-10.66	-36.62	-31.35	-36.87	-32.96	6.44	8.27
Moderate Intensity Earthquakes									
Liberty2475	Max	35.98	37.98	62.59	83.63	62.97	86.66	3.91	2.80
Liberty2475	Min	-30.2	-38.01	-96.14	-85.42	-96.4	-87.8	2.46	3.10
El Centro	Max	40.39	37.97	53.36	72.83	53.46	76.02	4.61	3.19
El Centro	Min	-24.19	-25.12	-58.64	-39.93	-58.62	-41.44	4.05	6.57
Fortpayne2475	Max	20.22	4.4	34.09	15.89	34.1	16.87	7.22	14.38
Fortpayne2475	Min	-8.32	-7.26	-19.77	-18.1	-19.98	-18.61	11.88	14.64
High Intensity Earthquakes									
Northridge	Max	75.83	63.15	214.52	132.09	215.63	137.12	1.14	1.77
Northridge	Min	-135.43	-77.29	-381.15	-164.05	-381.22	-169.47	**0.62**	1.61
Charleston2475	Max	169.06	434.28	372.57	698.79	377.23	741.96	**0.65**	**0.33**
Charleston2475	Min	-297.34	-270.06	-681.67	-292.84	-682.16	-304.49	**0.35**	**0.89**

Table 5-16: Maximum sliding of pedestals LCS P1-1, 1-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	2.26	1.25	2.75	1.42	2.98	1.53	109.09	151.01
Lowndes475	Min	-2.52	-1.72	-2.91	-2.04	-3.09	-2.38	103.09	145.63
Lowndes2475	Max	1.84	0.91	2.49	1.31	3.19	1.57	120.48	141.07
Lowndes2475	Min	-2.33	-1.47	-2.64	-2.08	-3.07	-2.44	113.64	146.58
Liberty475	Max	2.26	1.25	2.75	1.42	2.98	1.53	109.09	151.01
Liberty475	Min	-2.52	-1.72	-2.91	-2.04	-3.09	-2.38	103.09	145.63
Bartow475	Max	2.68	1.83	3.18	2.21	3.37	2.37	94.34	133.53
Bartow475	Min	-2.9	-2.62	-3.24	-3.47	-3.81	-3.68	92.59	118.11
Fortpayne475	Max	1.52	0.85	1.82	1.16	2.27	1.25	164.84	198.24
Fortpayne475	Min	-1.98	-1.24	-2.18	-1.65	-2.22	-1.89	137.61	202.70
Bartow2475	Max	3.82	2.37	3.99	2.34	3.81	2.54	75.19	118.11
Bartow2475	Min	-4.24	-4.92	-4.12	-4.18	-4.82	-4.55	70.75	93.36
Charleston475	Max	7.07	4.02	7.82	6.14	8.14	6.78	38.36	55.28
Charleston475	Min	-8.18	-4.43	-10.64	-5.7	-10.9	-6.04	28.20	41.28
Moderate Intensity Earthquakes									
Liberty2475	Max	12.41	7.7	15.97	12.23	19.16	14.86	18.79	23.49
Liberty2475	Min	-18.26	-9.78	-22.88	-12.45	-22.36	-12.35	13.11	20.13
El Centro	Max	9.34	5.02	11.65	8.45	13.73	10.79	25.75	32.77
El Centro	Min	-18.22	-6.03	-21.51	-7.57	-19.47	-6.59	13.95	23.11
Fortpayne2475	Max	4.61	2.65	5.02	3.31	6.16	3.73	59.76	73.05
Fortpayne2475	Min	-5.87	-3.63	-7.33	-4.35	-7.57	-4.65	40.93	59.45
High Intensity Earthquakes									
Northridge	Max	25.66	12.71	31.26	15.82	31.1	15.89	9.60	14.47
Northridge	Min	-47.75	-15.31	-55.73	-19.4	-50.72	-20.67	5.38	8.87
Charleston2475	Max	30.72	41.32	44.02	56.71	54.09	59.29	6.82	8.32
Charleston2475	Min	-90.54	-27.14	-121.9	-35.38	-105.03	-37.05	2.46	4.28

Table 5-17: Maximum sliding of pedestals LCS P2-1, 3-1

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	4.31	1	4.15	1.35	3.46	1.32	69.61	130.06
Lowndes475	Min	-0.81	-1.18	-1.36	-1.97	-2.29	-2.18	220.59	196.51
Lowndes2475	Max	4.15	1.47	4.37	1.99	3.33	1.85	68.65	135.14
Lowndes2475	Min	-0.71	-0.85	-1.08	-1.49	-1.63	-1.7	277.78	276.07
Liberty475	Max	4.31	1	4.15	1.35	3.46	1.32	69.61	130.06
Liberty475	Min	-0.81	-1.18	-1.36	-1.97	-2.29	-2.18	220.59	196.51
Bartow475	Max	5.04	1.34	6.54	1.78	6.13	1.55	45.87	73.41
Bartow475	Min	-2.62	-1.62	-4.08	-2.36	-4.9	-2.55	73.53	91.84
Fortpayne475	Max	2.8	0.96	3.58	1.3	3.27	1.17	83.80	137.61
Fortpayne475	Min	-0.76	-0.39	-1.3	-0.59	-1.79	-0.85	230.77	251.40
Bartow2475	Max	6.22	1.71	6.01	2.46	6.54	2.99	48.23	68.81
Bartow2475	Min	-3.4	-2.9	-4.3	-2.82	-4.89	-3.07	69.77	92.02
Charleston475	Max	8.79	3.89	11.44	5.5	12.55	6.02	26.22	35.86
Charleston475	Min	-7.4	-4.37	-9.53	-5.11	-9.83	-5.91	31.48	45.78
Moderate Intensity Earthquakes									
Liberty2475	Max	13.52	7.17	22.6	10.08	25.71	12.01	13.27	17.50
Liberty2475	Min	-14.48	-8.46	-19.09	-11.01	-20.64	-11.6	15.72	21.80
El Centro	Max	11.08	3.88	18.14	5.55	19.19	5.91	16.54	23.45
El Centro	Min	-12.44	-5.1	-15.35	-6.39	-15.97	-7.53	19.54	28.18
Fortpayne2475	Max	6.47	2.38	7.21	2.66	7.5	2.95	41.61	60.00
Fortpayne2475	Min	-4.24	-2.86	-5.9	-3.35	-6.21	-3.54	50.85	72.46
High Intensity Earthquakes									
Northridge	Max	28.88	5.9	42.04	8.06	43.39	8	7.14	10.37
Northridge	Min	-42.19	-15.61	-58.02	-21.13	-59.82	-23.63	5.17	7.52
Charleston2475	Max	63.32	39.86	86.04	51.72	95.33	56.42	3.49	4.72
Charleston2475	Min	-76.41	-37.61	-106.64	-50.46	-108.56	-53.11	2.81	4.15

Table 5-18: Maximum sliding of pedestals LCS P2-2, 3-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	3.38	0.6	3.5	0.55	2.83	0.41	85.71	159.01
Lowndes475	Min	-0.93	-0.31	-1.11	-0.32	-1.54	-0.44	270.27	292.21
Lowndes2475	Max	3.87	0.85	3.72	0.84	3	0.39	77.52	150.00
Lowndes2475	Min	-0.68	-0.26	-0.69	-0.29	-2.17	-0.67	434.78	207.37
Liberty475	Max	3.38	0.6	3.5	0.55	2.83	0.41	85.71	159.01
Liberty475	Min	-0.93	-0.31	-1.11	-0.32	-1.54	-0.44	270.27	292.21
Bartow475	Max	5.5	1.1	6.17	1.02	4.82	0.74	48.62	93.36
Bartow475	Min	-2.32	-0.85	-2.8	-0.9	-3.42	-1.09	107.14	131.58
Fortpayne475	Max	3.03	0.64	3.27	0.6	2.3	0.47	91.74	195.65
Fortpayne475	Min	-0.59	-0.27	-0.57	-0.3	-1.56	-0.59	508.47	288.46
Bartow2475	Max	6.85	1.87	7.54	1.89	5.94	1.66	39.79	75.76
Bartow2475	Min	-2.85	-1.08	-2.98	-1.15	-4.68	-1.34	100.67	96.15
Charleston475	Max	9.69	2.86	11.65	2.9	11.53	3.08	25.75	39.03
Charleston475	Min	-5	-2.06	-6.71	-2.19	-9.34	-2.87	44.71	48.18
Moderate Intensity Earthquakes									
Liberty2475	Max	16.71	6.33	19.27	6.78	21.3	7.77	8.67	12.10
Liberty2475	Min	-12.46	-4.87	-15.3	-5.18	-17.26	-5.73	15.57	21.13
El Centro	Max	16.31	3.26	19.97	3.79	20.64	3.84	19.61	26.07
El Centro	Min	-12.26	-2.79	-14.05	-2.71	-15.43	-3.25	15.02	21.80
Fortpayne2475	Max	6.85	1.8	6.98	1.83	6.12	1.53	21.35	29.16
Fortpayne2475	Min	-3.14	-1.42	-3.61	-1.42	-5.04	-1.6	42.98	73.53
High Intensity Earthquakes									
Northridge	Max	28.67	6.38	34.02	6.3	35.86	7.03	8.82	12.55
Northridge	Min	-38.19	-13.12	-45.58	-13.38	-47.63	-14.16	6.58	9.45
Charleston2475	Max	66.87	50.55	78.34	54.79	86.34	53.62	3.83	5.21
Charleston2475	Min	-65.75	-37.71	-80.41	-39.74	-79.51	-38.91	3.73	5.66

Table 5-19: Maximum sliding of pedestals NCDG P1-1, 1-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	2.78	1.28	3.82	1.69	4.25	1.9	78.53	105.88
Lowndes475	Min	-2.82	-2.18	-3.7	-3.08	-3.99	-3.48	81.08	112.78
Lowndes2475	Max	2.9	1.62	3.59	1.85	3.84	1.54	83.57	117.19
Lowndes2475	Min	-2.46	-2.92	-2.73	-3.14	-2.75	-2.95	109.89	163.64
Liberty475	Max	2.99	1.77	3.04	1.54	2.8	1.75	98.68	160.71
Liberty475	Min	-2.59	-3.04	-2.89	-3.04	-2.78	-2.78	103.81	161.87
Bartow475	Max	4.73	2.54	5.96	4.64	6.31	5.12	50.34	71.32
Bartow475	Min	-7.98	-4.33	-10.78	-5.36	-11.25	-5.27	27.83	40.00
Fortpayne475	Max	1.97	0.89	2.28	1.32	2.62	1.4	131.58	171.76
Fortpayne475	Min	-1.8	-1.38	-2.03	-2.35	-2.12	-2.44	147.78	212.26
Bartow2475	Max	4.45	3.43	4.92	4.56	5.48	4.79	60.98	82.12
Bartow2475	Min	-5.82	-4.17	-6.45	-5.34	-5.86	-5.02	46.51	76.79
Charleston475	Max	5.41	8.03	4.77	9.19	7.43	8.61	55.45	60.57
Charleston475	Min	-15.95	-9.45	-18.49	-10.37	-16.34	-9.58	16.22	27.54
Moderate Intensity Earthquakes									
Liberty2475	Max	28.3	18.16	34.62	26.11	37.19	26.16	8.67	12.10
Liberty2475	Min	-33.48	-13.72	-44.18	-17.11	-44.66	-19.3	6.79	10.08
El Centro	Max	13.1	13.26	14.4	15.25	18.5	13.92	20.83	24.32
El Centro	Min	-22.09	-6.72	-22.32	-6.36	-20.91	-6.87	13.44	21.52
Fortpayne2475	Max	5.71	5.14	7.24	6.97	8.56	6.86	41.44	52.57
Fortpayne2475	Min	-9.72	-5.11	-11.5	-6.04	-10.69	-6.06	26.09	42.10
High Intensity Earthquakes									
Northridge	Max	65.37	21.42	78.83	25.04	73.82	26	3.81	6.10
Northridge	Min	-105.55	-18.62	-133.51	-27.02	-120.17	-28.84	2.25	3.74
Charleston2475	Max	99.25	102.28	125.12	160.3	127.87	146.94	2.40	3.52
Charleston2475	Min	-247.82	-58.86	-291.59	-82.04	-229.89	-75.03	1.03	1.96

Table 5-20: Maximum sliding of pedestals NCDG P2-1, 3-1

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	5.81	1.3	5.18	1.63	4.8	1.54	51.64	93.75
Lowndes475	Min	-1.08	-1.02	-0.78	-1.68	-1.1	-1.73	277.78	409.09
Lowndes2475	Max	5.53	2	5.31	1.76	4.33	1.23	54.25	103.93
Lowndes2475	Min	-2.84	-1.86	-1.85	-1.94	-1.48	-1.71	105.63	304.05
Liberty475	Max	4.62	1.52	6.1	1.7	5.57	1.59	49.18	80.79
Liberty475	Min	-1.97	-2.45	-2.66	-2.72	-3.05	-2.3	112.78	147.54
Bartow475	Max	8.96	2.61	10.52	4.25	11.75	4.82	28.52	38.30
Bartow475	Min	-6.32	-4.2	-8.07	-4.52	-8.24	-3.89	37.17	54.61
Fortpayne475	Max	5.44	1.23	6.53	1.6	6.1	1.39	45.94	73.77
Fortpayne475	Min	-2.11	-1.38	-3	-1.84	-4.01	-1.79	100.00	112.22
Bartow2475	Max	7.95	2.95	8.18	3.65	7.98	3.72	36.67	56.39
Bartow2475	Min	-6.25	-3.77	-8.63	-3.93	-8.91	-3.77	34.76	50.51
Charleston475	Max	9.38	5.3	12.93	4.86	12.72	4.74	23.20	35.38
Charleston475	Min	-9.63	-7.17	-13.16	-8.55	-14.82	-8.9	22.80	30.36
Moderate Intensity Earthquakes									
Liberty2475	Max	22.81	11.8	28.18	14.68	31.09	16.21	10.65	14.47
Liberty2475	Min	-30.01	-17.45	-40.33	-22.5	-39.63	-21.53	7.44	11.36
El Centro	Max	15.98	4.94	21.13	7.59	21.5	8.02	14.20	20.93
El Centro	Min	-12.76	-8.07	-20.4	-12.17	-21.54	-11.63	14.71	20.89
Fortpayne2475	Max	10.67	4.21	12.51	5.39	12.57	5.94	23.98	35.80
Fortpayne2475	Min	-7.99	-4.34	-9.31	-5.58	-9.31	-5.45	32.22	48.34
High Intensity Earthquakes									
Northridge	Max	66.54	13.57	90.62	16.36	91.79	18.28	3.31	4.90
Northridge	Min	-124.56	-44.9	-169.38	-51.85	-162.56	-49.23	1.77	2.77
Charleston2475	Max	124.5	75.2	166.22	114.4	179.49	119.79	1.80	2.51
Charleston2475	Min	-245.37	-114.51	-318.87	-150.86	-299.33	-149.39	**0.94**	1.50

Table 5-21: Maximum sliding of pedestals NCDG P2-2, 3-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	5.11	1.01	5.31	0.96	4.37	0.74	56.50	102.97
Lowndes475	Min	-1.02	-0.34	-1.2	-0.36	-1.31	-0.37	250.00	343.51
Lowndes2475	Max	4.8	0.75	4.73	0.74	3.95	0.67	62.50	113.92
Lowndes2475	Min	-1.26	-0.56	-1.47	-0.54	-1.64	-0.61	204.08	274.39
Liberty475	Max	5.08	1	5.39	1.02	4.38	1	55.66	102.74
Liberty475	Min	-1.48	-0.68	-1.69	-0.7	-1.92	-0.61	177.51	234.38
Bartow475	Max	9.66	2.22	10.56	2.19	10.15	2.56	28.41	44.33
Bartow475	Min	-4.64	-2.12	-6.07	-2.17	-7.13	-2.26	49.42	63.11
Fortpayne475	Max	4.87	0.84	5.04	0.78	4.38	0.71	59.52	102.74
Fortpayne475	Min	-1.27	-0.51	-1.56	-0.51	-1.81	-0.57	192.31	248.62
Bartow2475	Max	9.06	2.91	9.55	2.98	8.06	2.27	31.41	55.83
Bartow2475	Min	-3.67	-1.66	-4.54	-1.73	-4.83	-1.69	66.08	93.17
Charleston475	Max	11.87	3.92	13.42	3.98	12.39	3.42	22.35	36.32
Charleston475	Min	-10.75	-4.8	-13.15	-5.05	-14.55	-5.27	22.81	30.93
Moderate Intensity Earthquakes									
Liberty2475	Max	21.44	11.87	24.02	12.47	24.87	11.57	12.49	18.09
Liberty2475	Min	-30.13	-11.86	-36.08	-12.62	-35.73	-12.83	8.31	12.59
El Centro	Max	12.83	6.41	15.55	7.5	19.05	9.02	19.29	23.62
El Centro	Min	-18.13	-4.57	-21.56	-4.76	-21.36	-4.59	13.91	21.07
Fortpayne2475	Max	11.64	3.25	12.94	3.32	12.67	3.38	23.18	35.52
Fortpayne2475	Min	-5.88	-2.75	-7.11	-2.9	-8.17	-2.9	42.19	55.08
High Intensity Earthquakes									
Northridge	Max	66.23	19.35	79.84	19.64	83.55	21.01	3.76	5.39
Northridge	Min	-118.66	-34.1	-140.63	-34.62	-134.93	-33.3	2.13	3.34
Charleston2475	Max	129.1	94.29	155.69	95.67	164.57	79.51	1.93	2.73
Charleston2475	Min	-208	-74.83	-249.03	-72.57	-242.56	-64.41	1.20	1.86

5.1.5. Pounding analysis of the superstructure

According to Tables 5.22 to 5.24, the 'C/D' ratios for pounding analysis of the superstructure are having little difference when compared to response of the NCS models. So the pounding behavior does not indicate much change. This is because the mass difference is not much between NCS and LCS models as stated earlier.

Table 5-22: Pounding analysis of superstructure LCS P1-1, 1-2

Ground Motion	Abutment (mm)	Deck joint (mm)	Axial(kN) (at abutment)	Axial(kN) (at joint)	Max. 'C/D' ratio	
					Abutment	Deck Joint
Low Intensity Earthquakes						
Lowndes475	1.82	7.11	0	0	13.96	3.57
Lowndes2475	2.62	7.06	0	0	9.69	3.60
Liberty475	1.82	7.11	0	0	13.96	3.57
Bartow475	3.56	7.55	0	0	7.13	3.36
Fortpayne475	2.11	3.71	0	0	12.04	6.85
Bartow2475	8.49	20.75	0	0	2.99	1.22
Charleston475	10.45	41.58	0	3.24	2.43	**0.61**
Moderate Intensity Earthquakes						
Liberty2475	25.97	66.11	0.11	8.14	**0.98**	**0.38**
El Centro	31.1	49.6	1.14	4.84	**0.82**	**0.51**
Fortpayne2475	7.96	20.42	0	0	3.19	1.24
High Intensity Earthquakes						
Northridge	115.96	177.92	18.11	30.51	**0.22**	**0.14**
Charleston2475	161.03	549.71	27.13	104.86	**0.16**	**0.05**

Table 5-23: Pounding analysis of superstructure LCS P2-1, 3-1

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	1.62	10.4	0	0	15.68	2.44
Lowndes2475	1.21	11.4	0	0	20.99	2.23
Liberty475	1.62	10.4	0	0	15.68	2.44
Bartow475	5.55	15.25	0	0	4.58	1.67
Fortpayne475	0.78	6.56	0	0	32.56	3.87
Bartow2475	9.62	16.03	0	0	2.64	1.58
Charleston475	9.47	26.23	0	0.17	2.68	**0.97**
Moderate Intensity Earthquakes						
Liberty2475	12.25	36.9	0	2.3	2.07	**0.69**
El Centro	14.99	35.27	0	1.97	1.69	**0.72**
Fortpayne2475	7.21	17.04	0	0	3.52	1.49
High Intensity Earthquakes						
Northridge	50.66	117.8	5.05	18.48	**0.50**	**0.22**
Charleston2475	71.94	180.96	9.31	31.11	**0.35**	**0.14**

Table 5-24: Pounding analysis of superstructure LCS P2-2, 3-2

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	2.61	9.1	0	0	9.73	2.79
Lowndes2475	4.57	10.19	0	0	5.56	2.49
Liberty475	2.61	9.1	0	0	9.73	2.79
Bartow475	2.41	11.41	0	0	10.54	2.23
Fortpayne475	0.65	6.57	0	0	39.08	3.87
Bartow2475	5.73	18.58	0	0	4.43	1.37
Charleston475	5.93	25.87	0	0.09	4.28	**0.98**
Moderate Intensity Earthquakes						
Liberty2475	6.86	32.24	0	1.37	3.70	**0.79**
El Centro	10.13	31.39	0	1.2	2.51	**0.81**
Fortpayne2475	5.74	15.82	0	0	4.43	1.61
High Intensity Earthquakes						
Northridge	44.64	100.97	3.85	15.12	**0.57**	**0.25**
Charleston2475	58.11	168.29	6.54	28.58	**0.44**	**0.15**

According to Tables 5-25-5-27, the force transmitted to the superstructure has increased significantly due to pounding in NCDG models. It is having lower 'C/D' ratios when compared to the NCS models. This is because the difference in mass of the superstructure is more for NCDG and NCS models than between NCS and LCS models. The pounding is definitely critical factor for heavier superstructure even for low intensity earthquakes like Charleston475.

Table 5-25: Pounding analysis of superstructure NCDG P1-1, 1-2

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	3.23	11.9	0	0	7.86	2.13
Lowndes2475	4.6	9.35	0	0	5.52	2.72
Liberty475	6.66	10.3	0	0	3.81	2.47
Bartow475	9.81	38.3	0	2.58	2.59	0.66
Fortpayne475	4.06	6.38	0	0	6.26	3.98
Bartow2475	10.64	21.85	0	0	2.39	1.16
Charleston475	34.02	44.73	1.73	3.87	**0.75**	**0.57**
Moderate Intensity Earthquakes						
Liberty2475	74.61	145.53	9.84	24.03	**0.34**	**0.17**
El Centro	69.14	95.06	8.75	13.93	**0.37**	**0.27**
Fortpayne2475	20.47	33.77	0	1.67	1.24	**0.75**
High Intensity Earthquakes						
Northridge	192.49	362.62	33.42	67.44	**0.13**	**0.07**
Charleston2475	646.3	811.15	124.18	157.15	**0.04**	**0.03**

Table 5-26: Pounding analysis of superstructure NCDG P2-1, 3-1

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	5.7	11.97	0	0	4.46	2.12
Lowndes2475	9.12	13.99	0	0	2.79	1.82
Liberty475	3.57	11.27	0	0	7.11	2.25
Bartow475	10.08	23.05	0	0	2.52	1.10
Fortpayne475	2.33	14.71	0	0	10.90	1.73
Bartow2475	9.07	22.95	0	0	2.80	1.11
Charleston475	17.79	44.43	0	3.81	1.43	**0.57**
Moderate Intensity Earthquakes						
Liberty2475	37.05	74.93	2.33	9.91	**0.69**	**0.34**
El Centro	27.59	56.53	0.44	6.23	**0.92**	**0.45**
Fortpayne2475	12.6	22.41	0	0	2.02	1.13
High Intensity Earthquakes						
Northridge	155.36	263.31	25.99	47.58	**0.16**	**0.10**
Charleston2475	339.64	476.15	62.85	90.15	**0.07**	**0.05**

Table 5-27: Pounding analysis of superstructure NCDG P2-2, 3-2

Ground Motion	Abutment (mm)	Deck joint (mm)	Axial(kN) (at abutment)	Axial(kN) (at joint)	Max. 'C/D' ratio	
					Abutment	Deck Joint
Low Intensity Earthquakes						
Lowndes475	2.71	13.77	0	0	9.37	1.84
Lowndes2475	2.17	9.2	0	0	11.71	2.76
Liberty475	2.49	9.67	0	0	10.20	2.63
Bartow475	4.76	17.71	0	0	5.34	1.43
Fortpayne475	2.12	7.62	0	0	11.98	3.33
Bartow2475	5.51	12.68	0	0	4.61	2.00
Charleston475	11.69	38.59	0	2.64	2.17	**0.66**
Moderate Intensity Earthquakes						
Liberty2475	30.09	73.6	0.94	9.64	**0.84**	**0.35**
El Centro	24.16	44.08	0	3.74	1.05	**0.58**
Fortpayne2475	8.16	18.67	0	0	3.11	1.36
High Intensity Earthquakes						
Northridge	135.64	247.13	22.05	44.35	**0.19**	**0.10**
Charleston2475	295.19	477.58	53.96	90.44	**0.09**	**0.05**

5.1.6. Summary of analysis results

The LCS models are generally having larger 'C/D' ratios and the NCDG models are having lesser 'C/D' ratios as compared to the NCS (baseline) models for most of the parameters. This indicates that mass is a critical factor in assessing the performance of these pedestals. If the weight if the superstructure is heavy, like the NCDG models, then it is not suitable for both high and moderate seismic zones, as the capacity to demand ratio is too low to be retrofitted. While, these pedestals if installed with lightweight concrete decks would not be sufficient for high seismic zones, however, they will perform well for moderate seismic zones if retrofitted. However, for low seismic zones, the pedestals can be used for either LCS or NCDG models.

5.2. EFFECT OF STIFFNESS OF DECK-GAP ELEMENT

The effect of pounding at the expansion joints has been detrimental for the bridge performance in past earthquakes. For instance, there was damage to the Interstate 5 and State Road 14 Interchange during the 1994 Northridge Earthquake. While previous research has been conducted to study the effects of pounding, the results vary from work to work, leading to no definite conclusion [18]. This research explores the effect of pounding for all twenty one number of the bridge models. In this parametric study the stiffness of the deck gap element has been incremented to ten times the original deck gap stiffness used in baseline models (2200 kN/m), where the effect of pounding is studied. To this end, the stiffness of the deck-gap elements is varied to evaluate the effects of pounding given varying deck-gap element stiffness.

5.2.1. Modal characteristics of the bridge

The time periods of first four modes of vibration for the NCS and NCS-DG models are almost same as indicated in Table 5-28. But the fundamental mode for all pedestal configurations is transverse instead of longitudinal which is because the stiffness of deck gap element has been increased, which is aligned in the longitudinal direction. The second mode is longitudinal and third and fourth modes are rotational and transverse mode for end spans, which are the same as that of NCS models.

Table 5-28: Structural period of first four modes (NCS-DG models)

Mode	Time Period (s)		
	NCS-DG P1-1, 1-2	NCS-DG P2-1, 3-1	NCS-DG P2-2, 3-2
1	0.83	0.79	0.94
2	0.70	0.63	0.60
3	0.45	0.43	0.53
4	0.43	0.40	0.49

5.2.2. Maximum displacement of pedestals

As indicated in Tables 5-29-5-31, the maximum displacement of the pedestals is exceeded for the NCS models and NCS-DG models, where the ‘C/D’ ratios are very similar to each other. This indicates that the increment of deck gap stiffness does not affect the displacement of the pedestals, which is also observed in past research done in this field [18].

Table 5-29: Maximum displacement of pedestals NCS-DG P1-1, 1-2

Ground Motion	**Type**	**BTJ-2a**		**BTJ-2b**		**BTJ-4**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	2	1.64	7.06	4.13	7.07	4.78	6.29	17.27
Lowndes475	Min	-1.17	-3.86	-4.27	-8.77	-4.38	-10.1	10.15	8.17
Lowndes2475	Max	4.24	4.67	9.97	6.92	9.94	8.1	4.46	10.19
Lowndes2475	Min	-2.3	-11.28	-6.72	-13.36	-6.92	-15.37	6.42	5.37
Liberty475	Max	3.58	3.75	10.75	6.58	10.72	7.73	4.13	10.68
Liberty475	Min	-2.52	-8.54	-6.82	-13.79	-7.05	-15.65	6.30	5.27
Bartow475	Max	4.9	4.28	15.03	11.02	15.11	13.98	2.94	5.90
Bartow475	Min	-2.69	-8.52	-9.13	-16.99	-9.33	-19.78	4.76	4.17
Fortpayne475	Max	3.05	2.73	7.31	4.11	7.36	4.62	6.04	17.87
Fortpayne475	Min	-1.7	-5.67	-3.94	-6.3	-4.12	-6.54	10.79	12.62
Bartow2475	Max	12.42	8.45	18.73	14.87	18.87	17.15	2.36	4.81
Bartow2475	Min	-7.15	-18.05	-9.88	-19.27	-9.95	-23.11	4.47	3.57
Charleston475	Max	14	11.11	24.86	20.15	25.23	23.57	1.76	3.50
Charleston475	Min	-10.46	-18.98	-29.93	-23.98	-30.19	-27.14	1.47	3.04
Moderate Intensity Earthquakes									
Liberty2475	Max	14.39	32.15	68.84	52.34	69.65	62.32	**0.64**	1.32
Liberty2475	Min	-50.58	-31.27	-94.16	-43.16	-95.08	-50.17	**0.47**	1.65
El Centro	Max	20.78	33.47	51.07	54.25	50.72	62.81	**0.87**	1.31
El Centro	Min	-43.1	-31.79	-81.59	-36.63	-81.45	-37.68	**0.54**	2.19
Fortpayne2475	Max	9.1	10.16	17.29	12.09	17.59	14.57	2.53	5.67
Fortpayne2475	Min	-5.92	-14.06	-13.97	-17.34	-14.24	-19.44	3.12	4.25
High Intensity Earthquakes									
Northridge	Max	49.92	58.63	152.02	84.44	151.17	104.25	**0.29**	**0.79**
Northridge	Min	-108.97	-58.17	-183.13	-66.76	-184.12	-74.29	**0.24**	1.11
Charleston2475	Max	108.04	153.85	396.99	347.24	393.88	387.99	**0.11**	**0.21**
Charleston2475	Min	-314.12	-66.14	-661.89	-158.41	-651.73	-183.3	**0.07**	**0.45**

Table 5-30: Maximum displacement of pedestals NCS-DG P2-1, 3-1

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	5.13	1.57	13.74	3.74	13.55	4.37	2.59	11.62
Lowndes475	Min	-0.54	-0.85	-3.88	-2.97	-3.92	-3.86	9.07	13.16
Lowndes2475	Max	11.48	3.74	15.38	5.41	15.1	6.56	2.31	7.74
Lowndes2475	Min	-1.08	-3.63	-3.93	-7.7	-3.97	-8.79	8.96	5.78
Liberty475	Max	10.9	2.67	13.22	3.83	12.98	4.79	2.69	10.61
Liberty475	Min	-1.1	-2.92	-3.67	-8.07	-3.73	-9.05	9.53	5.61
Bartow475	Max	13.61	3.33	19.47	5.84	19.35	6.39	1.83	7.95
Bartow475	Min	-2.12	-5.94	-9.51	-10.68	-9.62	-12.29	3.70	4.13
Fortpayne475	Max	7.69	2.6	12.97	3.86	12.77	4.77	2.74	10.65
Fortpayne475	Min	-0.8	-2.8	-3.06	-4.24	-3.14	-5.24	11.32	9.69
Bartow2475	Max	12.58	7.55	17.06	8.83	17.08	11.41	2.08	4.45
Bartow2475	Min	-5.55	-13.55	-8.32	-10.34	-8.37	-12.54	4.25	3.75
Charleston475	Max	17.94	10.42	29.66	21.11	29.77	23.51	1.19	2.16
Charleston475	Min	-11.07	-13.11	-24.63	-21.33	-24.87	-24.17	1.43	2.10
Moderate Intensity Earthquakes									
Liberty2475	Max	27.63	23.92	55.52	34.82	56.06	40.96	**0.63**	1.24
Liberty2475	Min	-18.68	-18.76	-52.42	-50.77	-53.42	-57.54	**0.67**	**0.88**
El Centro	Max	18.78	20.59	51.34	34.54	50.73	41.78	**0.69**	1.22
El Centro	Min	-16.88	-18.42	-39.51	-27.63	-39.78	-32.89	**0.89**	1.54
Fortpayne2475	Max	16.33	5.28	23.3	10.42	23.38	12.32	1.52	4.12
Fortpayne2475	Min	-5.89	-9.88	-11.95	-14.25	-12.08	-16.28	2.94	3.12
High Intensity Earthquakes									
Northridge	Max	40.36	29.71	112.65	33.54	112.41	38.58	**0.32**	1.32
Northridge	Min	-70.38	-38.74	-162.03	-77.88	-160.33	-90.33	**0.22**	**0.56**
Charleston2475	Max	74.2	112.82	209.63	198.93	213.43	239.29	**0.17**	**0.21**
Charleston2475	Min	-128.6	-80.05	-291.17	-254.83	-293.65	-289.85	**0.12**	**0.18**

Table 5-31: Maximum displacement of pedestals NCS-DG P2-2, 3-2

Ground Motion	**Type**	**BTJ-2a**		**BTJ-2b**		**BTJ-4**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	6.6	0.8	12.86	0.87	12.65	0.84	6.91	58.39
Lowndes475	Min	-0.83	-0.27	-3.25	-0.63	-3.35	-0.99	26.53	51.31
Lowndes2475	Max	12.54	0.99	11.68	2.3	11.48	2.59	7.09	19.61
Lowndes2475	Min	-3.22	-0.36	-2.61	-2.39	-2.72	-3.07	27.61	16.55
Liberty475	Max	10.48	0.63	11.52	1.06	11.34	1.46	7.72	34.79
Liberty475	Min	-1.44	-0.41	-3.35	-2.38	-3.39	-2.86	26.22	17.76
Bartow475	Max	11.84	1.17	19.88	1.16	19.72	1.76	4.47	28.86
Bartow475	Min	-2.58	-1.44	-7.83	-4.63	-7.84	-5.82	11.34	8.73
Fortpayne475	Max	8.77	0.54	11.36	0.67	11.04	1.11	7.82	45.77
Fortpayne475	Min	-0.69	-1.43	-2.63	-2.45	-2.68	-2.95	33.17	17.22
Bartow2475	Max	13.72	1.28	16.41	6.55	16.24	7.75	5.42	6.55
Bartow2475	Min	-2.65	-4.09	-5.99	-7.74	-6.13	-9.17	14.50	5.54
Charleston475	Max	17.71	3.31	34.19	12.17	34.13	14.33	2.60	3.55
Charleston475	Min	-6.19	-3.67	-20.89	-14.65	-21.18	-16.1	4.20	3.16
Moderate Intensity Earthquakes									
Liberty2475	Max	27.45	12.53	56.21	40.18	56.44	44.16	1.57	1.15
Liberty2475	Min	-10.16	-11.18	-42.65	-47.03	-43.45	-53.56	2.05	**0.95**
El Centro	Max	26.72	8.59	52.67	44.84	52.01	51.07	1.69	**0.99**
El Centro	Min	-12.96	-7.35	-32.75	-19.75	-32.9	-24.97	2.70	2.03
Fortpayne2475	Max	16.76	1.25	21.38	6.9	21.13	8.09	4.16	6.28
Fortpayne2475	Min	-3.19	-5.68	-9.58	-6.55	-9.51	-7.44	9.28	6.83
High Intensity Earthquakes									
Northridge	Max	34.84	18.29	100	57.1	100.11	65.01	**0.89**	**0.78**
Northridge	Min	-69.44	-48.86	-146.85	-95.51	-147.11	-108.36	**0.60**	**0.47**
Charleston2475	Max	65.79	170.33	203.26	540.85	204.45	598.24	**0.43**	**0.08**
Charleston2475	Min	-121.81	-128.89	-276.39	-303.73	-276.2	-341.2	**0.32**	**0.15**

5.2.3. Maximum force transmitted to pedestals

According to Tables 5-32-5-34, ‘C/D’ ratios for the NCS models and NCS-DG models are almost same. This indicates that the increment of deck gap stiffness does not affect the force transmitted to the pedestals.

5.2.4. Maximum sliding of pedestals

The ‘C/D’ ratios are having safe value for all the cases as indicated in Tables 5-35-5-37. Similar to the NCS models, sliding seems to not be of much concern provided adequate seat width (W) is available.

5.2.5. Pounding analysis of the superstructure

According to Tables 5-38-5-40, the ‘C/D’ ratios for pounding analysis of the superstructure are much lower when compared to NCS models indicating excessive forces transmitted to adjacent superstructure due to pounding.

Table 5-32: Maximum force transmitted to pedestals NCS-DG P1-1, 1-2

Ground Motion	**Type**	**B-2a**		**B-2b**		**B-4**		**Max. 'C/D' ratio**	
		Shear (y-y)	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Y-Y**	**X-X**
Low Intensity Earthquakes									
Lowndes475	Max	12.03	12.69	3.79	5.27	11.63	14.38	28.85	8.71
Lowndes475	Min	-7.97	-4.28	-1.45	-2.03	-8.46	-6.01	50.64	48.58
Lowndes2475	Max	20.48	20.39	10.93	14.75	17.52	23.66	16.95	5.30
Lowndes2475	Min	-11.4	-6.65	-3.76	-5.86	-12.63	-10.17	33.92	28.71
Liberty475	Max	19.67	19.19	9.21	13.03	19.04	23.31	17.65	5.38
Liberty475	Min	-12.51	-6.81	-4.1	-4.22	-13.19	-9.51	32.48	30.70
Bartow475	Max	26.78	25	13.32	12.42	27.07	27.38	12.82	4.58
Bartow475	Min	-16.87	-8.44	-5.54	-4.46	-18.47	-16.3	23.19	17.91
Fortpayne475	Max	12.34	11.92	6.88	8.13	15.27	15.16	22.73	8.27
Fortpayne475	Min	-8	-3.03	-3.23	-3.03	-8.49	-3.93	50.46	74.29
Bartow2475	Max	28.28	26.4	28.09	22.47	28.88	28.87	12.02	4.34
Bartow2475	Min	-22.67	-12.36	-15.19	-8.79	-27.89	-22.57	15.36	12.94
Charleston475	Max	33.56	28.79	28.48	24.93	35.83	30.95	9.69	4.05
Charleston475	Min	-36.36	-15.84	-16.5	-11.1	-39.5	-25.98	10.85	11.24
Moderate Intensity Earthquakes									
Liberty2475	Max	91.64	56	38.54	32.64	111.56	79.96	3.11	1.57
Liberty2475	Min	-89.4	-56.81	-29.8	-20.42	-97.35	-108.61	4.40	2.69
El Centro	Max	77.62	61.25	37.68	35.54	108.8	83.74	3.19	1.50
El Centro	Min	-76.53	-56.82	-25	-25.99	-84.75	-110.05	5.05	2.65
Fortpayne2475	Max	29.22	24.91	22.06	24.43	29.52	27.29	11.76	4.59
Fortpayne2475	Min	-21.73	-9.55	-11	-7.59	-25.02	-16.2	17.12	18.02
High Intensity Earthquakes									
Northridge	Max	113.46	88.55	87.95	60.22	113.46	128.61	3.06	**0.97**
Northridge	Min	-148.59	-174.68	-29.68	-99.54	-160.88	-231.21	2.66	1.26
Charleston2475	Max	113.55	357.43	113.46	125.38	113.6	481.18	3.06	**0.26**
Charleston2475	Min	-300.33	-690.66	-100.04	-128.66	-354.68	-845.48	1.21	**0.35**

Table 5-33: Maximum force transmitted to pedestals NCS-DG P2-1, 3-1

Ground Motion	**Type**	**B-2a**		**B-2b**		**B-4**		**Max. 'C/D' ratio**	
		Shear (y-y)	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Y-Y**	**X-X**
Low Intensity Earthquakes									
Lowndes475	Max	7.56	2.41	10.71	6.05	10.8	8.99	21.81	18.19
Lowndes475	Min	-0.34	-10.49	-0.55	-12.6	-6.34	-13.63	32.24	9.98
Lowndes2475	Max	9.26	6.48	11.5	10.78	11.01	15.91	20.48	10.28
Lowndes2475	Min	-0.94	-13.56	-0.52	-17.19	-8.81	-19.22	23.20	7.08
Liberty475	Max	8.07	4.87	11.2	11.54	11.19	13.72	21.03	11.92
Liberty475	Min	-0.85	-12.62	-0.43	-17.35	-5.98	-19.34	34.18	7.03
Bartow475	Max	12.34	7.7	16	12.9	18.3	14.84	12.87	11.02
Bartow475	Min	-0.44	-15.48	-10.49	-19.32	-20.57	-23.22	9.94	5.86
Fortpayne475	Max	8.47	4.58	10.43	6.91	9.61	11.29	22.58	14.49
Fortpayne475	Min	-1.19	-12.39	-0.49	-13.81	-5.38	-15.31	38.00	8.88
Bartow2475	Max	12.35	15.33	15.11	17.35	24.09	21.22	9.78	7.71
Bartow2475	Min	-0.6	-21.97	-8.59	-19.22	-21.41	-26.47	9.55	5.14
Charleston475	Max	20.9	18.95	41.99	32.51	47.61	52.25	4.95	3.13
Charleston475	Min	-9.9	-19.85	-41.6	-29.85	-59.5	-42.26	3.44	3.22
Moderate Intensity Earthquakes									
Liberty2475	Max	27.8	30.45	88.88	70.09	102.99	80.83	2.29	2.02
Liberty2475	Min	-13.08	-24.31	-84.61	-78.28	-95.11	-103.51	2.15	1.31
El Centro	Max	26.59	29.99	75.14	72.44	91.55	84.35	2.57	1.94
El Centro	Min	-14.08	-25.06	-89.34	-51.5	-116.74	-70.81	1.75	1.92
Fortpayne2475	Max	13.07	13.34	18.65	17.72	23.65	23.76	9.96	6.88
Fortpayne2475	Min	-0.22	-19.1	-14.1	-21.87	-35.44	-28.6	5.77	4.76
High Intensity Earthquakes									
Northridge	Max	86.85	59.87	168.84	84.14	214.72	78.2	1.10	1.94
Northridge	Min	-50.73	-47.36	-226.17	-112.87	-245.49	-167.45	**0.83**	**0.81**
Charleston2475	Max	117.91	167.65	230.53	310.34	288.04	443.5	**0.82**	**0.37**
Charleston2475	Min	-89.33	-81.34	-420.08	-366.9	-480.82	-498.48	**0.43**	**0.27**

Table 5-34: Maximum force transmitted to pedestals NCS-DG P2-2, 3-2

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	7.51	3.1	10.49	7.06	9.65	6.55	23.47	34.37
Lowndes475	Min	-0.01	-10.54	-1.36	-12.23	-6.96	-12.08	34.10	22.27
Lowndes2475	Max	12.44	6.25	10.47	13.55	8.66	14.1	19.79	17.21
Lowndes2475	Min	-0.91	-12.13	-0.88	-13.17	-4.62	-13.22	51.37	20.61
Liberty475	Max	7.57	6.18	10.66	11.74	10.62	11.79	23.10	20.58
Liberty475	Min	0	-11.99	-0.67	-13.4	-4.27	-13.41	55.58	20.31
Bartow475	Max	9.6	9.29	19.67	12.29	25.23	12.98	9.76	18.69
Bartow475	Min	-0.01	-12.73	-11.22	-15.01	-22.74	-16.04	10.44	16.98
Fortpayne475	Max	6.37	8.77	8.91	10.87	9.78	11.04	25.17	21.98
Fortpayne475	Min	0	-13.12	-0.1	-13.79	-3.72	-13.78	63.79	19.75
Bartow2475	Max	11.81	11.17	17.46	17.12	23.58	18.45	10.44	13.15
Bartow2475	Min	-2.49	-14.51	-7.23	-20.05	-23.49	-21.74	10.10	12.53
Charleston475	Max	20.39	14.75	46.78	22.33	44.14	24.89	5.26	9.75
Charleston475	Min	-6.7	-14.39	-40.24	-24.49	-51.48	-25.52	4.61	10.67
Moderate Intensity Earthquakes									
Liberty2475	Max	31	20.09	91.91	37.05	101.38	40.4	2.43	6.01
Liberty2475	Min	-10.29	-18.64	-99.77	-44.77	-112.75	-53.59	2.10	5.08
El Centro	Max	22.35	17.56	75.31	39.28	98.4	45.2	2.50	5.37
El Centro	Min	-8.64	-16.3	-86.65	-32.55	-148.3	-36.02	1.60	7.56
Fortpayne2475	Max	14.8	12.05	26.64	17.11	32.73	19.78	7.52	12.27
Fortpayne2475	Min	-5.85	-15.69	-15.72	-17.16	-34.05	-19.61	6.97	13.89
High Intensity Earthquakes									
Northridge	Max	84.56	27.58	176.19	59.11	214.8	71.06	1.15	3.41
Northridge	Min	-19.33	-42.6	-250.17	-121.25	-243.82	-158.57	**0.95**	1.72
Charleston2475	Max	126.16	124.62	263.91	268.97	303.71	309.96	**0.81**	**0.78**
Charleston2475	Min	-110.28	-138.42	-579.73	-448.45	-515.28	-546.83	**0.41**	**0.50**

Table 5-35: Maximum sliding of pedestals NCS-DG P1-1, 1-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	1.41	0.79	1.82	1.01	1.91	1.11	164.84	235.60
Lowndes475	Min	-1.53	-1.28	-1.77	-1.89	-1.89	-2	169.49	238.10
Lowndes2475	Max	2.2	1.12	2.8	1.63	2.94	1.81	107.14	153.06
Lowndes2475	Min	-2.05	-1.96	-2.52	-2.69	-3.04	-3.05	119.05	148.03
Liberty475	Max	2.14	1.11	2.65	1.56	2.59	1.66	113.21	173.75
Liberty475	Min	-2.32	-2.13	-2.75	-2.89	-3.04	-3.19	109.09	148.03
Bartow475	Max	3.2	1.36	4.07	2.35	4.26	3.04	73.71	105.63
Bartow475	Min	-3.16	-2.02	-3.58	-3.43	-3.88	-3.8	83.80	115.98
Fortpayne475	Max	1.88	0.87	2.29	1.14	2.3	1.17	131.00	195.65
Fortpayne475	Min	-1.42	-0.9	-1.65	-1.4	-1.89	-1.46	181.82	238.10
Bartow2475	Max	4.93	3.45	5.26	4.08	5.2	3.82	57.03	86.54
Bartow2475	Min	-4.43	-4.03	-4.6	-3.96	-4.11	-4.66	65.22	109.49
Charleston475	Max	6.23	3.68	7.38	5.04	7.64	5.36	40.65	58.90
Charleston475	Min	-7.15	-5	-8.42	-5.54	-9.11	-5.76	35.63	49.40
Moderate Intensity Earthquakes									
Liberty2475	Max	13.42	9.51	18.57	12.33	21.67	14.12	16.16	20.77
Liberty2475	Min	-25.95	-10.78	-29.39	-11.99	-26.64	-13.16	10.21	16.89
El Centro	Max	9.8	7.29	11.85	10.05	14.07	11.56	25.32	31.98
El Centro	Min	-21.17	-6.97	-24.25	-8.79	-20.68	-8.57	12.37	21.76
Fortpayne2475	Max	4.83	3.04	5.79	3.53	5.61	3.46	51.81	80.21
Fortpayne2475	Min	-4.22	-2.94	-4.67	-3.64	-5.49	-4.21	64.24	81.97
High Intensity Earthquakes									
Northridge	Max	32.08	18.21	40.5	20.76	38.85	19.23	7.41	11.58
Northridge	Min	-47.23	-18.71	-53.12	-17.93	-47.15	-21.06	5.65	9.54
Charleston2475	Max	76.29	63.86	99.25	84.17	98.3	83.2	3.02	4.58
Charleston2475	Min	-122.22	-37.2	-147.24	-47.82	-109.9	-48.87	2.04	4.09

Table 5-36: Maximum sliding of pedestals NCS-DG P2-1, 3-1

Ground Motion	**Type**	**TTJ-2a**		**TTJ-2b**		**TTJ-3**		**Max. 'C/D' ratio**	
		X	**Y**	**X**	**Y**	**X**	**Y**	**Bent 'a'**	**Bent 'b'**
Low Intensity Earthquakes									
Lowndes475	Max	3.06	0.84	4.58	0.99	4.18	1.03	65.50	107.66
Lowndes475	Min	-1.03	-0.56	-1.71	-0.8	-2.15	-0.96	175.44	209.30
Lowndes2475	Max	4.89	1.46	5.44	1.71	4.2	1.63	55.15	107.14
Lowndes2475	Min	-0.78	-1.33	-1.26	-1.79	-2.09	-1.91	238.10	215.31
Liberty475	Max	4.15	1	4.52	1.25	3.7	1.18	66.37	121.62
Liberty475	Min	-1.24	-1.19	-1.72	-1.87	-2.1	-1.97	174.42	214.29
Bartow475	Max	5.68	1.78	7.02	2.1	6.21	1.95	42.74	72.46
Bartow475	Min	-2.53	-2.34	-4	-2.89	-4.39	-2.95	75.00	102.51
Fortpayne475	Max	3.74	1.09	4.63	1.2	3.88	1.18	64.79	115.98
Fortpayne475	Min	-0.65	-0.91	-1.18	-1.1	-1.82	-1.31	254.24	247.25
Bartow2475	Max	5.27	2.7	6.16	2.54	5.65	2.55	48.70	79.65
Bartow2475	Min	-2.43	-3.44	-3.15	-3.1	-3.68	-2.53	95.24	122.28
Charleston475	Max	9.16	3.61	10.83	5.56	12.01	6.38	27.70	37.47
Charleston475	Min	-7.26	-5.13	-9.87	-6.14	-10.96	-6.07	30.40	41.06
Moderate Intensity Earthquakes									
Liberty2475	Max	16.42	8.44	21.53	9.92	23.65	11.5	13.93	19.03
Liberty2475	Min	-17.79	-10.52	-23.84	-14.52	-24.94	-15.37	12.58	18.04
El Centro	Max	11.08	5.69	18.7	8.01	19.3	9.07	16.04	23.32
El Centro	Min	-11.88	-6.61	-16.57	-7.72	-17.88	-8.2	18.11	25.17
Fortpayne2475	Max	6.19	2.03	8.23	3.04	7.94	3.36	36.45	56.68
Fortpayne2475	Min	-4.67	-3.49	-5.44	-4.14	-5.59	-4.13	55.15	80.50
High Intensity Earthquakes									
Northridge	Max	33.52	7.21	48.18	9.59	49.76	9.65	6.23	9.04
Northridge	Min	-53.1	-18.31	-67.67	-24.51	-65.31	-25.82	4.43	6.89
Charleston2475	Max	85.74	42.35	108.87	55.15	112.72	59.66	2.76	3.99
Charleston2475	Min	-99.91	-51.26	-127.54	-71.01	-123.89	-73.54	2.35	3.63

Table 5-37: Maximum sliding of pedestals NCS-DG P2-2, 3-2

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	3.5	0.81	4.01	0.77	3.28	0.61	74.81	137.20
Lowndes475	Min	-0.77	-0.23	-1.01	-0.24	-1.75	-0.43	297.03	257.14
Lowndes2475	Max	4.32	0.88	4.06	0.85	2.87	0.41	69.44	156.79
Lowndes2475	Min	-0.79	-0.27	-0.84	-0.29	-1.65	-0.59	357.14	272.73
Liberty475	Max	3.47	0.65	3.8	0.59	2.89	0.39	78.95	155.71
Liberty475	Min	-1.3	-0.42	-1.51	-0.44	-1.69	-0.49	198.68	266.27
Bartow475	Max	6.06	1.29	6.62	1.23	5.9	1.06	45.32	76.27
Bartow475	Min	-2.37	-0.85	-2.86	-0.9	-3.39	-1.14	104.90	132.74
Fortpayne475	Max	3.31	0.55	3.7	0.5	2.87	0.36	81.08	156.79
Fortpayne475	Min	-0.67	-0.37	-1	-0.38	-1.47	-0.47	300.00	306.12
Bartow2475	Max	5.08	1.19	5.53	1.28	4.78	1.38	54.25	94.14
Bartow2475	Min	-1.88	-1.12	-2.37	-1.19	-2.9	-1.25	126.58	155.17
Charleston475	Max	10.37	3.02	12.03	3.09	11.59	3.23	24.94	38.83
Charleston475	Min	-6.27	-2.56	-7.93	-2.75	-9.53	-3.23	37.83	47.22
Moderate Intensity Earthquakes									
Liberty2475	Max	17.83	6.31	20.53	6.57	21.76	7.22	14.61	20.68
Liberty2475	Min	-14.74	-6.54	-17.81	-7.08	-19.74	-7.59	16.84	22.80
El Centro	Max	15.94	4.7	19.27	5.35	19.54	5.5	15.57	23.03
El Centro	Min	-11.04	-3.26	-12.92	-3.28	-14.46	-3.54	23.22	31.12
Fortpayne2475	Max	6.32	1.56	7.28	1.63	6.76	1.63	41.21	66.57
Fortpayne2475	Min	-3.04	-1.42	-3.6	-1.43	-4.37	-1.49	83.33	102.97
High Intensity Earthquakes									
Northridge	Max	33.92	8.4	40.34	8.24	42.37	9.06	7.44	10.62
Northridge	Min	-52.52	-16.95	-59.48	-16.77	-55.4	-15.34	5.04	8.12
Charleston2475	Max	80.72	63.08	92.9	69.01	96.07	67.35	3.23	4.68
Charleston2475	Min	-93.32	-46.19	-107	-48.45	-94.97	-44.23	2.80	4.74

Table 5-38: Pounding analysis of superstructure NCS-DG P1-1, 1-2

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	1.12	3.29	0	0	22.68	7.72
Lowndes2475	2.38	6.49	0	0	10.67	3.91
Liberty475	2.51	5.7	0	0	10.12	4.46
Bartow475	2.77	8.02	0	0	9.17	3.17
Fortpayne475	1.71	3.7	0	0	14.85	6.86
Bartow2475	6.91	12.93	0	0	3.68	1.96
Charleston475	10.57	31.71	0	12.62	2.40	**0.80**
Moderate Intensity Earthquakes						
Liberty2475	50.47	49.83	50.14	48.85	**0.50**	**0.51**
El Centro	42.77	48.85	34.74	46.91	**0.59**	**0.52**
Fortpayne2475	6.28	15.01	0	0	4.04	1.69
High Intensity Earthquakes						
Northridge	109.68	127.25	168.57	203.7	**0.23**	**0.20**
Charleston2475	313.63	370.19	576.47	689.58	**0.08**	**0.07**

Table 5-39: Pounding analysis of superstructure NCS-DG P2-1, 3-1

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	0.51	4.79	0	0	49.80	5.30
Lowndes2475	1.01	9.88	0	0	25.15	2.57
Liberty475	1.03	7.99	0	0	24.66	3.18
Bartow475	2.07	14.26	0	0	12.27	1.78
Fortpayne475	0.68	7.43	0	0	37.35	3.42
Bartow2475	5.44	13.93	0	0	4.67	1.82
Charleston475	10.97	25.08	0	0	2.32	1.01
Moderate Intensity Earthquakes						
Liberty2475	18.73	36.8	0	22.8	1.36	**0.69**
El Centro	16.99	34.11	0	17.42	1.49	**0.74**
Fortpayne2475	5.71	17.5	0	0	4.45	1.45
High Intensity Earthquakes						
Northridge	69.92	108.19	89.03	165.57	**0.36**	**0.23**
Charleston2475	125.77	164.52	200.74	278.24	**0.20**	**0.15**

Table 5-40: Pounding analysis of superstructure NCS-DG P2-2, 3-2

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. ‘C/D’ ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	0.77	5.14	0	0	32.99	4.94
Lowndes2475	3.17	7.77	0	0	8.01	3.27
Liberty475	1.43	7.39	0	0	17.76	3.44
Bartow475	2.48	12.29	0	0	10.24	2.07
Fortpayne475	0.57	6.42	0	0	44.56	3.96
Bartow2475	2.51	12.4	0	0	10.12	2.05
Charleston475	5.87	22.13	0	0	4.33	1.15
Moderate Intensity Earthquakes						
Liberty2475	9.86	35.03	0	19.27	2.58	0.73
El Centro	12.83	31.73	0	12.65	1.98	0.80
Fortpayne2475	3.12	14.39	0	0	8.14	1.77
High Intensity Earthquakes						
Northridge	69.6	97.77	88.41	144.74	**0.36**	**0.26**
Charleston2475	117.09	156.51	183.37	262.22	**0.22**	**0.16**

5.2.6. Summary of analysis results

In the baseline models (NCS), 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). This assumption is made to get the longitudinal mode as the fundamental mode of vibration for the bridge, which is a general expected behavior. But for the models having larger deck gap stiffness (NCS-DG models), the stiffness of the deck gap element is increased to 22000 kN/m.

From the analysis results it is observed that there is not much of a difference in the ‘C/D’ ratios between the NCS-DG models and the NCS models, but the pounding force is considerably higher for higher deck gap stiffness. It is again expected behavior as the more is the stiffness of the element the more are the forces induced in it, so flexibility is essential for a structural component. It proves the point why the expansion joints should not be too stiff than the adjacent bridge components. Generally, as a rule of thumb the stiffness of the deck gap element should not be 1000 times more than the stiffness of adjacent superstructure [18]. Hence, there is no significant change in behavior of pedestals and higher stiffness of expansion joints should be avoided to reduce the risk of large forces induced in the superstructure due to pounding.

5.3. EFFECT OF VARYING COLUMN HEIGHTS

The height of the columns supporting the superstructure is another crucial factor for the seismic behavior of the bridge. The stiffness of the column is increased by the height and this can significantly change the output. In this parametric study, the heights of the columns are changed. As shown in Fig. 5-1, the end bents are having height of 7 m, the middle bent is having 21 m columns, and other two bents are having 14 m columns.

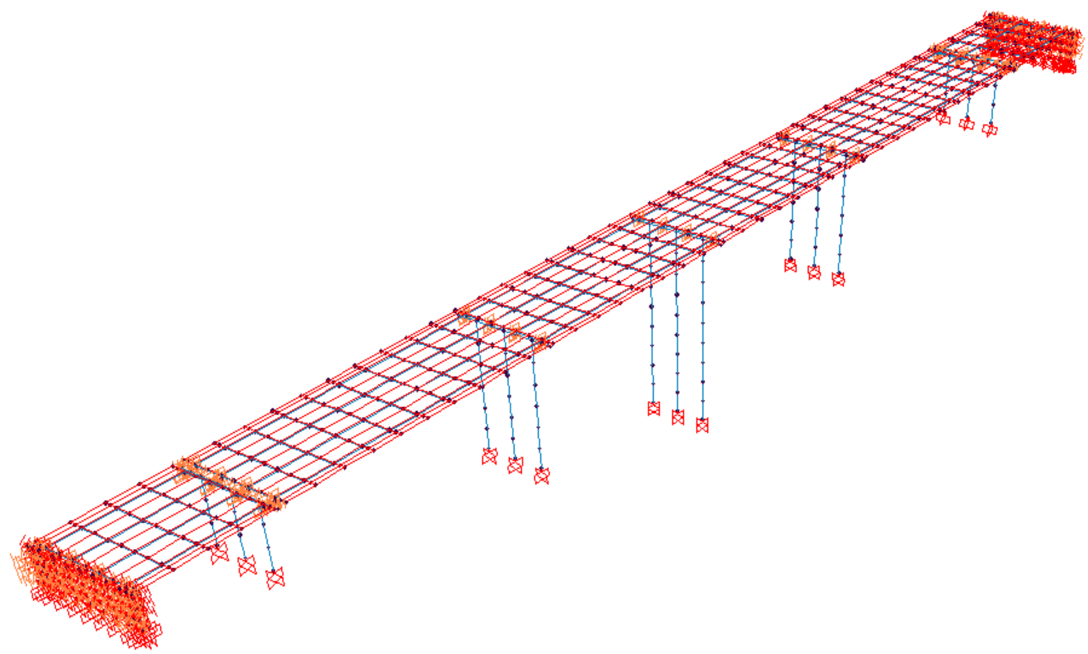


Figure 5-1: Three dimensional view of the bridge having varying column heights

5.3.1. Modal characteristics of the bridge

The time periods of first four modes of vibration for the NCS-C models is shown in Table 5-41. The fundamental modes of vibration are the same as the corresponding cases of the baseline models but the structural period has increased almost by 30%. This is because by increasing the height of the columns, the stiffness is reduced and the structure has become more flexible and thus has relatively larger time period.

Table 5-41: Structural period of first four modes (NCS-C models)

Mode	Time Period (s)		
	NCS P1-1, 1-2-C	NCS P2-1, 3-1-C	NCS P2-2, 3-2-C
1	1.23	1.13	1.16
2	1.02	0.97	0.99
3	0.52	0.45	0.56
4	0.48	0.43	0.51

5.3.2. Maximum displacement of pedestals

According to Tables 5-42-5-44, when compared to the results of NCS models the ‘C/D’ ratios have shown a significant decrease. Thus usage of the steel pedestals is not recommended with high columns for high and moderate intensity earthquakes. Even for low intensity earthquakes, it should be verified whether the steel pedestals require retrofitting or not.

Table 5-42: Maximum displacement of pedestals NCS P1-1, 1-2-C

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes									
Lowndes475	Max	2.06	1.66	12.36	6.01	12.65	8.18	3.51	10.09
Lowndes475	Min	-1.79	-3.97	-8.38	-8.66	-8.55	-10.3	5.20	8.01
Lowndes2475	Max	4.09	4.58	11.64	5.11	11.88	6.99	3.74	11.81
Lowndes2475	Min	-2.68	-11.49	-7.98	-6.69	-8.15	-7.94	5.45	7.18
Liberty475	Max	3.83	4.05	10.27	5.6	10.51	7.56	4.23	10.92
Liberty475	Min	-2.63	-8.79	-7.01	-8.39	-7.21	-9.87	6.17	8.36
Bartow475	Max	6.95	4.52	17.38	13.25	17.8	16.5	2.50	5.00
Bartow475	Min	-5.66	-8.72	-22.44	-16.38	-22.71	-19.82	1.96	4.16
Fortpayne475	Max	3.92	2.78	9	4.29	9.2	5.91	4.83	13.97
Fortpayne475	Min	-2.68	-5.86	-8.51	-8.06	-8.72	-9.72	5.10	8.49
Bartow2475	Max	13.59	7.79	16.22	11.78	16.5	15.24	2.69	5.42
Bartow2475	Min	-11.7	-17.32	-11.09	-12.16	-11.22	-14.64	3.80	4.77
Charleston475	Max	12.56	11.29	25.27	24.58	25.91	29.93	1.72	2.76
Charleston475	Min	-16.41	-19.21	-46.15	-35.48	-46.44	-43.58	**0.96**	1.89
Moderate Intensity Earthquakes									
Liberty2475	Max	16.72	34.11	105.97	77.16	107.39	95.53	**0.41**	**0.86**
Liberty2475	Min	-49.58	-34.19	-154.5	-65.33	-157.61	-87.52	**0.28**	**0.94**
El Centro	Max	14.13	31.15	76.17	57.85	75.9	72.1	**0.58**	1.14
El Centro	Min	-48.86	-30.99	-101.53	-58.26	-100.52	-75.85	**0.44**	1.09
Fortpayne2475	Max	12.33	10.08	26.2	18.56	26.61	23.91	1.67	3.45
Fortpayne2475	Min	-7.65	-14.22	-35.86	-27.75	-36.51	-33.27	1.22	2.48
High Intensity Earthquakes									
Northridge	Max	49.14	64.34	266.95	116.26	266.61	142.35	**0.17**	**0.58**
Northridge	Min	-138.4	-52.61	-470.52	-93	-470.34	-140.39	**0.09**	**0.59**
Charleston2475	Max	41.7	164.48	473.64	569.46	459.85	694.59	**0.09**	**0.12**
Charleston2475	Min	-239.1	-65.08	-941.45	-273.86	-933.51	-411.03	**0.05**	**0.20**

Table 5-43: Maximum displacement of pedestals NCS P2-1, 3-1-C

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	8.1	1.36	17.72	5.49	17.74	7.13	2.00	7.12
Lowndes475	Min	-0.71	-1.13	-13.25	-6.08	-13.63	-8.57	2.61	5.93
Lowndes2475	Max	13.89	3.13	13.64	6.94	13.47	9.23	2.56	5.50
Lowndes2475	Min	-4.35	-3.17	-6.3	-7.66	-6.34	-10.42	5.61	4.88
Liberty475	Max	12.62	2.17	12.79	5.67	12.74	7.69	2.78	6.61
Liberty475	Min	-2.05	-2.29	-5.74	-6.64	-5.93	-9.35	6.00	5.43
Bartow475	Max	13.89	3.8	30.76	13.11	31.02	16.48	1.15	3.08
Bartow475	Min	-7.88	-6.33	-21.95	-14.28	-22.35	-18.12	1.59	2.80
Fortpayne475	Max	10.66	2.24	10.77	4.59	10.74	5.84	3.30	8.70
Fortpayne475	Min	-1.29	-2.28	-5.74	-3.84	-5.77	-5.35	6.16	9.50
Bartow2475	Max	15	7.35	22.55	9.99	22.54	13.28	1.58	3.83
Bartow2475	Min	-8.04	-12.7	-13.3	-13.04	-13.37	-16.77	2.66	3.03
Charleston475	Max	13.83	10.63	28.6	20.12	29.4	26.19	1.21	1.94
Charleston475	Min	-12.97	-12.56	-35.91	-26.74	-36.69	-34.35	**0.97**	1.48
Moderate Intensity Earthquakes									
Liberty2475	Max	21.32	22.36	70.77	47.38	72.57	63.6	**0.49**	**0.80**
Liberty2475	Min	-15.21	-19.53	-85.66	-68.33	-87.36	-85.45	**0.41**	**0.59**
El Centro	Max	18.39	18.47	68.77	33.65	67.84	47.06	**0.52**	1.08
El Centro	Min	-17.98	-16.44	-59.52	-48.33	-58.62	-61.98	**0.60**	**0.82**
Fortpayne2475	Max	17.3	5	34.22	13.42	34.42	16.95	1.03	3.00
Fortpayne2475	Min	-8.37	-10.2	-27.07	-13.72	-27.49	-17.13	1.29	2.97
High Intensity Earthquakes									
Northridge	Max	40.12	41.04	188.88	49.06	189.98	70.06	**0.19**	**0.73**
Northridge	Min	-102.78	-46.15	-320.66	-139.9	-323.26	-179.47	**0.11**	**0.28**
Charleston2475	Max	105.76	135.86	387.88	406.68	403.9	524.31	**0.09**	**0.10**
Charleston2475	Min	-161.83	-113.02	-614.89	-498.64	-624.83	-645.33	**0.06**	**0.08**

Table 5-44: Maximum displacement of pedestals NCS P2-2, 3-2-C

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	8.96	0.94	17.03	1.38	16.95	2.7	5.22	18.81
Lowndes475	Min	-0.8	-0.42	-6.98	-1.38	-7.07	-2.53	12.57	20.08
Lowndes2475	Max	12.63	0.97	16.48	3.42	16.24	4.87	5.39	10.43
Lowndes2475	Min	-4.03	-0.38	-5.21	-4.36	-5.34	-5.38	16.65	9.44
Liberty475	Max	10.88	0.84	14.47	2.61	14.29	3.91	6.14	12.99
Liberty475	Min	-1.8	-0.49	-6.44	-3.28	-6.44	-4.5	13.80	11.29
Bartow475	Max	11.41	1.53	25.99	5.9	25.98	7.7	3.42	6.60
Bartow475	Min	-1.79	-1.84	-11.94	-6.16	-12.15	-7.99	7.32	6.36
Fortpayne475	Max	10.14	0.53	11.54	2.02	11.5	3.16	7.70	16.08
Fortpayne475	Min	-0.75	-2.31	-4.11	-2.42	-4.24	-3.82	20.96	13.30
Bartow2475	Max	14.68	1.15	21.58	7.75	21.47	9.77	4.12	5.20
Bartow2475	Min	-2.15	-4.49	-8.12	-7.75	-8.15	-9.9	10.91	5.13
Charleston475	Max	14.83	2.37	33.92	13.58	34.13	16.55	2.60	3.07
Charleston475	Min	-7.19	-4.35	-32.84	-24.57	-33.61	-29.23	2.64	1.74
Moderate Intensity Earthquakes									
Liberty2475	Max	22.74	11.61	67.37	64.87	68.21	74.97	1.30	**0.68**
Liberty2475	Min	-11.78	-14.23	-81.32	-75.75	-82.79	-91.72	1.07	**0.55**
El Centro	Max	24.03	6.92	60.52	48.72	59.93	56.29	1.47	**0.90**
El Centro	Min	-12.56	-7.19	-62.36	-41.46	-62.06	-47.14	1.43	1.08
Fortpayne2475	Max	17.53	1.41	34.02	11.18	34.06	14.48	2.61	3.51
Fortpayne2475	Min	-3.86	-5.78	-19.09	-13.14	-19.47	-15.86	4.57	3.20
High Intensity Earthquakes									
Northridge	Max	42.76	27.69	187.62	79.54	188.52	97.2	**0.47**	**0.52**
Northridge	Min	-75.59	-52.36	-300.46	-141.7	-302.14	-168.23	**0.29**	**0.30**
Charleston2475	Max	99.24	203.28	388.87	656.79	397.29	755.35	**0.22**	**0.07**
Charleston2475	Min	-157.06	-146.89	-592.41	-476.2	-602.74	-575.19	**0.15**	**0.09**

5.3.3. Maximum force transmitted to pedestals

According to Tables 5-45-5-47, the force transmitted to the pedestals has relatively increased when compared with the NCS models. This is because as the flexibility is increased, the structure displaces to greater extent and the corresponding force transmitted to the pedestals increases.

5.3.4. Maximum sliding of pedestals

The ‘C/D’ ratios for sliding of NCS-C models are having relatively much lower value than the NCS models as indicated in Tables 5-19-5-21. In fact for P2-1, 3-1 pedestal configuration, the ‘C/D’ ratio is less than one for Charleston2475 earthquake. Even for other cases, the sliding values are close to one and hence sliding the seat width (W) should be increased for corresponding critical cases.

5.3.5. Pounding analysis of the superstructure

According to Tables 5-51-5-53, the force transmitted to the superstructure has increased significantly due to pounding in NCS-C models. It is having much lower ‘C/D’ ratios when compared to NCS models. Therefore, pounding is definitely a critical factor when the superstructure is elevated on high columns even for low intensity earthquakes like Charleston475.

Table 5-45: Maximum force transmitted to pedestals NCS P1-1, 1-2-C

Ground Motion	**Type**	**B-2a**		**B-2b**		**B-4**		**Max. 'C/D' ratio**	
		Shear (y-y)	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Shear (y-y)**	**Shear (x-x)**	**Y-Y**	**X-X**
Low Intensity Earthquakes									
Lowndes475	Max	5.2	5.16	27.95	17.64	5.29	4.85	12.42	7.10
Lowndes475	Min	-2.2	-2.08	-13.85	-4.09	-4.63	-2.4	30.93	71.39
Lowndes2475	Max	12.75	14.43	27.94	13.93	4.19	5.94	12.42	8.68
Lowndes2475	Min	-4.81	-5.99	-13.02	-3.17	-2.94	-2.41	32.90	48.74
Liberty475	Max	11.01	13.22	23.59	16.84	4.38	5.92	14.71	7.44
Liberty475	Min	-4.58	-4.49	-11.61	-4.08	-3.97	-2.51	36.90	65.03
Bartow475	Max	18.11	12.7	31.58	25.98	9.34	10.52	10.99	4.82
Bartow475	Min	-7.82	-4.6	-27.04	-9.12	-6.79	-4.52	15.84	32.01
Fortpayne475	Max	10.22	8.45	28.04	12.54	4.31	5.04	12.38	9.99
Fortpayne475	Min	-4.16	-3.1	-9.77	-3.77	-3.57	-2.3	43.85	77.45
Bartow2475	Max	28.83	22.92	28.44	25.43	13.33	7.83	12.04	4.93
Bartow2475	Min	-16.91	-8.61	-19.61	-5.5	-9.27	-3.98	21.85	33.91
Charleston475	Max	29.64	25.32	41.9	25.67	28.04	23.18	8.28	4.88
Charleston475	Min	-18.46	-12.02	-54.8	-31.93	-9.39	-13.41	7.82	9.14
Moderate Intensity Earthquakes									
Liberty2475	Max	45.21	34.74	113.46	85.49	31.82	42.82	3.06	1.47
Liberty2475	Min	-38.13	-22.03	-120.91	-162.72	-17.32	-16.58	3.54	1.79
El Centro	Max	45.83	33.56	112.52	65.63	28.97	32.98	3.08	1.91
El Centro	Min	-36.47	-24.51	-105.5	-147.79	-16.6	-25.85	4.06	1.98
Fortpayne2475	Max	28.05	24.55	36.64	28.45	14.56	17.13	9.47	4.40
Fortpayne2475	Min	-14.12	-7.67	-42.33	-21.15	-6.75	-4.91	10.12	13.80
High Intensity Earthquakes									
Northridge	Max	113.46	67.19	113.46	126.84	111.02	114.7	3.06	**0.99**
Northridge	Min	-79.94	-141.57	-226.13	-391.24	-39.03	-46.2	1.89	**0.75**
Charleston2475	Max	113.46	135.81	113.49	614.59	113.46	352.36	3.06	**0.20**
Charleston2475	Min	-77.43	-183.84	-377.16	-1424.1	-105.11	-110.03	1.14	**0.21**

Table 5-46: Maximum force transmitted to pedestals NCS P2-1, 3-1-C

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	9.89	2.14	19.7	10.42	6.44	4.52	11.96	15.69
Lowndes475	Min	-0.19	-10.45	-14.99	-15.08	-1.35	-11.04	13.64	9.02
Lowndes2475	Max	12.6	5.71	13.87	14.75	8.83	3.31	16.98	11.09
Lowndes2475	Min	-0.57	-13.36	-3.87	-16.88	-2.33	-10.77	52.82	8.06
Liberty475	Max	10.89	4.64	13.26	13.54	7.78	3.13	17.76	12.08
Liberty475	Min	-0.23	-12.28	-0.49	-16.12	-1.39	-11.03	147.06	8.44
Bartow475	Max	14.14	7.77	38.61	20.25	10.6	3.86	6.10	8.08
Bartow475	Min	-5.33	-15.01	-41.28	-22.41	-3.01	-10.87	4.95	6.07
Fortpayne475	Max	9.64	4.14	13.42	8.63	6.53	3.31	17.55	18.95
Fortpayne475	Min	-0.31	-11.91	-0.49	-13.61	-1.32	-11.09	154.86	9.99
Bartow2475	Max	15.81	14.81	20.72	17.81	8.69	6.53	11.37	9.18
Bartow2475	Min	-5.96	-21.75	-20.28	-21.7	-1.56	-12.81	10.08	6.25
Charleston475	Max	17.33	18.56	73.69	43.92	16.53	7.06	3.20	3.72
Charleston475	Min	-13.03	-19.98	-61.17	-40.28	-12.57	-14.53	3.34	3.38
Moderate Intensity Earthquakes									
Liberty2475	Max	29.11	32.27	116.36	83.56	41.84	16.27	2.02	1.96
Liberty2475	Min	-17.3	-25.2	-136.2	-105.47	-32.17	-31.18	1.50	1.29
El Centro	Max	38.42	30.7	101.78	71.48	37.38	18.14	2.31	2.29
El Centro	Min	-29.19	-26.85	-145.5	-79.96	-21.76	-23.39	1.40	1.70
Fortpayne2475	Max	17.18	13.03	50.48	20.94	16.9	6.56	4.67	7.81
Fortpayne2475	Min	-1.56	-19.26	-42.42	-21.54	-14.02	-13.31	4.82	6.31
High Intensity Earthquakes									
Northridge	Max	91.24	59.77	264.44	99.19	115.73	59.89	**0.89**	1.65
Northridge	Min	-72.26	-60.75	-465.96	-209.92	-88.92	-56.06	**0.44**	**0.65**
Charleston2475	Max	117.85	197.12	451.51	614.22	285.7	234.69	**0.52**	**0.27**
Charleston2475	Min	-193.71	-104.95	-1007.57	-719.77	-102.68	-257.85	**0.20**	**0.19**

Table 5-47: Maximum force transmitted to pedestals NCS P2-2, 3-2-C

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	9.9	2.97	19.08	12.17	4.64	6.26	12.90	19.94
Lowndes475	Min	-0.01	-10.23	-7.13	-12.27	-0.08	-9.76	33.28	22.20
Lowndes2475	Max	14.59	4.95	15.94	14.42	4.55	10.8	15.45	16.83
Lowndes2475	Min	-1.64	-12.02	-7.13	-15.35	-0.07	-12.48	33.28	17.75
Liberty475	Max	8.62	6.91	18.24	13.96	4.68	11.28	13.50	17.38
Liberty475	Min	-0.01	-12.03	-5.21	-14.11	-0.06	-12.43	45.55	19.31
Bartow475	Max	15.43	8.45	34.81	16.05	9.63	10.74	7.07	15.12
Bartow475	Min	-2.05	-13.01	-24.84	-16.86	-4.09	-12.92	9.55	16.16
Fortpayne475	Max	8.74	10.65	13.2	13.6	4.44	8.32	18.65	17.84
Fortpayne475	Min	-0.03	-13.84	-0.68	-13.08	-0.07	-12.17	348.99	19.68
Bartow2475	Max	17.05	11.1	24.97	18.17	14.05	11.01	9.86	13.35
Bartow2475	Min	-4	-15.1	-15.55	-19.55	-7.76	-13.48	15.26	13.93
Charleston475	Max	13.62	14.09	77.29	25.64	24.01	11.33	3.19	9.46
Charleston475	Min	-6.79	-14.15	-48.35	-32.27	-14.64	-14.5	4.91	8.44
Moderate Intensity Earthquakes									
Liberty2475	Max	33.41	20.46	125.9	55.77	39.24	29.56	1.96	4.35
Liberty2475	Min	-18.99	-19.4	-160.21	-80.74	-27.19	-37.31	1.48	3.37
El Centro	Max	32.48	18.31	112.96	42.75	33.37	29.3	2.18	5.68
El Centro	Min	-15.09	-16.74	-139.64	-41.1	-21.94	-25.26	1.70	6.63
Fortpayne2475	Max	19.28	12.72	51.94	21.19	13.54	11.44	4.74	11.45
Fortpayne2475	Min	-4.52	-15.22	-42.45	-23.33	-9.25	-13.61	5.59	11.68
High Intensity Earthquakes									
Northridge	Max	82.74	27.95	289.22	110.11	116.32	69.31	**0.85**	2.20
Northridge	Min	-33.35	-39.58	-615.61	-193.57	-82.98	-62.59	**0.39**	1.41
Charleston2475	Max	140.43	137.62	516.35	307.76	232.75	253.89	**0.48**	**0.79**
Charleston2475	Min	-152.36	-133.54	-1415.56	-705.31	-113.68	-289.28	**0.17**	**0.39**

Table 5-48: Maximum sliding of pedestals NCS P1-1, 1-2-C

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	2.29	0.9	3.11	1.4	9.41	5.21	96.46	47.82
Lowndes475	Min	-2.13	-1.36	-2.64	-2.02	-8.6	-6.27	113.64	52.33
Lowndes2475	Max	2.38	1.33	3.12	1.51	9.33	4.54	96.15	48.23
Lowndes2475	Min	-1.89	-2.35	-2.32	-2	-8.53	-4.86	129.31	52.75
Liberty475	Max	1.94	1.02	2.6	1.29	8.36	4.77	115.38	53.83
Liberty475	Min	-1.63	-1.71	-2.09	-1.77	-7.08	-5.79	143.54	63.56
Bartow475	Max	4.11	1.97	4.99	3.07	15.46	10.27	60.12	29.11
Bartow475	Min	-4.03	-2.33	-5.75	-3.55	-19.39	-12.06	52.17	23.21
Fortpayne475	Max	2.35	0.89	2.76	1.13	7.65	3.65	108.70	58.82
Fortpayne475	Min	-2.34	-1.39	-2.77	-1.96	-8.57	-5.95	108.30	52.51
Bartow2475	Max	4.52	2.49	5.09	2.86	13.13	8.97	58.94	34.27
Bartow2475	Min	-4.06	-3.82	-4.1	-3.23	-10.87	-8.25	73.17	41.40
Charleston475	Max	6.62	4.06	8.25	5.59	28.77	17.39	36.36	15.64
Charleston475	Min	-9.74	-5.63	-12.1	-7.97	-35.47	-26.46	24.79	12.69
Moderate Intensity Earthquakes									
Liberty2475	Max	18.8	11.88	27.08	15.63	89.51	57.44	11.08	5.03
Liberty2475	Min	-30.32	-12.69	-39.42	-17.6	-106.64	-56.09	7.61	4.22
El Centro	Max	10.03	7.27	16.09	10.5	55.87	37.12	18.65	8.05
El Centro	Min	-18.37	-7.65	-24.2	-12.4	-65.3	-40.08	12.40	6.89
Fortpayne2475	Max	5.29	3.19	6.57	4.41	19.99	14.51	45.66	22.51
Fortpayne2475	Min	-6.53	-3.65	-8.91	-6.06	-30.34	-20.69	33.67	14.83
High Intensity Earthquakes									
Northridge	Max	43.86	20.47	61.74	24.32	180.38	72.57	4.86	2.49
Northridge	Min	-76.47	-14.87	-103.19	-26.14	-235.38	-88.78	2.91	1.91
Charleston2475	Max	52.56	72.91	85.97	115.9	248.6	372.03	3.49	1.81
Charleston2475	Min	-141.2	-53.89	-194.47	-74.82	-492.08	-255.82	1.54	**0.91**

Table 5-49: Maximum sliding of pedestals NCS P2-1, 3-1-C

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	4.77	1.32	6.48	1.78	11.74	4.79	46.30	38.33
Lowndes475	Min	-2.44	-1.22	-4.78	-1.78	-12.54	-5.85	62.76	35.89
Lowndes2475	Max	5.26	1.29	4.69	1.69	7.35	5.44	57.03	61.22
Lowndes2475	Min	-1.41	-1	-1.51	-1.68	-6.2	-6.02	198.68	72.58
Liberty475	Max	4.82	1.15	4.73	1.43	7.35	4.44	62.24	61.22
Liberty475	Min	-1.23	-0.89	-1.71	-1.44	-6.67	-5.25	175.44	67.47
Bartow475	Max	7.45	2.63	10.11	3.73	22.54	11.08	29.67	19.96
Bartow475	Min	-4.59	-2.74	-7.83	-3.81	-19.46	-11.55	38.31	23.12
Fortpayne475	Max	4.52	1.15	4.31	1.5	7.15	3.74	66.37	62.94
Fortpayne475	Min	-0.99	-0.68	-1.23	-0.89	-5.23	-2.85	243.90	86.04
Bartow2475	Max	7.21	2.39	8.03	2.94	15.69	8.04	37.36	28.68
Bartow2475	Min	-4.96	-3.21	-5.63	-3.54	-13	-10.1	53.29	34.62
Charleston475	Max	8.16	3.74	11.14	5.27	27.37	16.18	26.93	16.44
Charleston475	Min	-6.05	-4.62	-12.66	-6.99	-34.71	-21.99	23.70	12.96
Moderate Intensity Earthquakes									
Liberty2475	Max	16.07	7.66	25.67	11.41	63.44	40.28	11.69	7.09
Liberty2475	Min	-21.32	-12.36	-33.34	-18.2	-77.66	-54.57	9.00	5.79
El Centro	Max	15.21	5.62	22.59	6.82	46.95	24.48	13.28	9.58
El Centro	Min	-13.25	-7.27	-21.05	-11.64	-46.65	-35.4	14.25	9.65
Fortpayne2475	Max	7.59	2.18	11.02	3.71	23.27	11.63	27.22	19.34
Fortpayne2475	Min	-5.59	-3.39	-9.98	-4.01	-24.67	-11.65	30.06	18.24
High Intensity Earthquakes									
Northridge	Max	51.79	16.43	77.09	12.89	181.52	33.7	3.89	2.48
Northridge	Min	-85.97	-31.13	-123.86	-41.36	-251.05	-110.75	2.42	1.79
Charleston2475	Max	110.78	71.78	166.98	107.68	427.05	328.89	1.80	1.05
Charleston2475	Min	-164.11	-89.38	-237.26	-133.64	-507.03	-402.09	1.26	**0.89**

Table 5-50: Maximum sliding of pedestals NCS P2-2, 3-2-C

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	4.85	1.04	5.54	0.98	10.2	2.05	54.15	44.12
Lowndes475	Min	-1.55	-0.46	-2.09	-0.47	-6.83	-1.79	143.54	65.89
Lowndes2475	Max	4.35	1.05	4.84	1.05	8.95	2.31	61.98	50.28
Lowndes2475	Min	-0.89	-0.47	-1.14	-0.55	-5.66	-2.46	263.16	79.51
Liberty475	Max	4.01	0.83	4.71	0.81	8.18	2.18	63.69	55.01
Liberty475	Min	-1.16	-0.48	-1.46	-0.52	-6.09	-2.37	205.48	73.89
Bartow475	Max	7.47	1.8	8.81	1.77	18.15	5.6	34.05	24.79
Bartow475	Min	-2.84	-1.11	-3.77	-1.18	-11.88	-4.57	79.58	37.88
Fortpayne475	Max	4.02	0.7	4.05	0.68	6.55	1.43	74.07	68.70
Fortpayne475	Min	-0.54	-0.46	-0.84	-0.48	-4.32	-1.8	357.14	104.17
Bartow2475	Max	6.82	1.5	7.47	1.52	13.33	5.23	40.16	33.76
Bartow2475	Min	-2.4	-1.2	-2.73	-1.24	-10.53	-4.91	109.89	42.74
Charleston475	Max	10.18	3.08	12.09	3.19	26.22	10.44	24.81	17.16
Charleston475	Min	-7.62	-3.57	-10.74	-3.92	-34.41	-16.87	27.93	13.08
Moderate Intensity Earthquakes									
Liberty2475	Max	17.98	8.51	22.56	9.38	57.58	37.83	13.30	7.82
Liberty2475	Min	-22.25	-9.58	-28.66	-10.47	-75.89	-46.05	10.47	5.93
El Centro	Max	16.11	5.97	19.61	6.56	46.42	24.42	15.30	9.69
El Centro	Min	-16.58	-5.47	-21.07	-6.01	-52.44	-24.44	14.24	8.58
Fortpayne2475	Max	9.26	2.54	10.89	2.64	23.67	9.04	27.55	19.01
Fortpayne2475	Min	-5.12	-2.34	-6.57	-2.45	-19.29	-9.08	45.66	23.33
High Intensity Earthquakes									
Northridge	Max	56.24	14.92	69.17	14.61	172.86	37.2	4.34	2.60
Northridge	Min	-86.06	-28.11	-106.19	-28.51	-246.57	-91.03	2.83	1.83
Charleston2475	Max	111.43	78.11	142.04	85.61	379.46	356.04	2.11	1.19
Charleston2475	Min	-162.36	-75.66	-204.39	-80.33	-480.64	-307.47	1.47	**0.94**

Table 5-51: Pounding analysis of superstructure NCS P1-1, 1-2-C

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	1.77	7.63	0	0	14.35	3.33
Lowndes2475	2.72	9.44	0	0	9.34	2.69
Liberty475	2.6	5.98	0	0	9.77	4.25
Bartow475	5.68	21.8	0	0	4.47	1.17
Fortpayne475	2.6	8.31	0	0	9.77	3.06
Bartow2475	11.5	14.12	0	0	2.21	1.80
Charleston475	16.34	44.81	0	3.88	1.55	**0.57**
Moderate Intensity Earthquakes						
Liberty2475	49.18	116.67	4.76	18.25	**0.52**	**0.22**
El Centro	48.87	78.55	4.69	10.63	**0.52**	**0.32**
Fortpayne2475	7.65	36.8	0	2.28	3.32	**0.69**
High Intensity Earthquakes						
Northridge	137.98	368.99	22.52	68.72	**0.18**	**0.07**
Charleston2475	238.77	747.88	42.67	144.5	**0.11**	**0.03**

Table 5-52: Pounding analysis of superstructure NCS P2-1, 3-1-C

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	0.72	15.23	0	0	35.28	1.67
Lowndes2475	4.35	13.1	0	0	5.84	1.94
Liberty475	2.05	13.78	0	0	12.39	1.84
Bartow475	7.85	22.89	0	0	3.24	1.11
Fortpayne475	1.3	11.49	0	0	19.54	2.21
Bartow2475	7.8	19.96	0	0	3.26	1.27
Charleston475	12.61	42.44	0	3.41	2.01	**0.60**
Moderate Intensity Earthquakes						
Liberty2475	14.7	72.71	0	9.46	1.73	**0.35**
El Centro	18.12	54.46	0	5.81	1.40	**0.47**
Fortpayne2475	8.25	26.15	0	0.15	3.08	**0.97**
High Intensity Earthquakes						
Northridge	101.88	237.12	15.3	42.34	**0.25**	**0.11**
Charleston2475	158.47	468.86	26.61	88.69	**0.16**	**0.05**

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Table 5-53: Pounding analysis of superstructure NCS P2-2, 3-2-C

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	0.7	10.25	0	0	36.29	2.48
Lowndes2475	3.97	10.5	0	0	6.40	2.42
Liberty475	1.7	11.5	0	0	14.94	2.21
Bartow475	1.6	16.92	0	0	15.88	1.50
Fortpayne475	0.6	9.92	0	0	42.33	2.56
Bartow2475	2	14.5	0	0	12.70	1.75
Charleston475	7.04	37.96	0	2.51	3.61	**0.67**
Moderate Intensity Earthquakes						
Liberty2475	11.3	72.47	0	9.42	2.25	**0.35**
El Centro	12.54	53.84	0	5.69	2.03	**0.47**
Fortpayne2475	3.9	19.97	0	0	6.51	1.27
High Intensity Earthquakes						
Northridge	75.04	225.63	9.93	40.05	**0.34**	**0.11**
Charleston2475	149.4	471	24.8	89.12	**0.17**	**0.05**

5.3.6. Summary of analysis results

The pedestals have lower 'C/D' ratios for most of the parameters, for the NCS-C models as compared to NCS models, which indicates that these pedestals are not safe with the bridge having higher columns. This can even cause unseating in one of the cases (Table 5-50). So for moderate and high intensity earthquakes, the compatibility of these pedestals with height of the bridge columns should be checked.

5.4. EFFECT OF SEISMIC RETROFIT MEASURE: CABLE RESTRAINERS

Cable restrainers are economical, relatively easy to install, and widely used. Some of their advantages are that the cables used are flexible enough to accommodate vertical and transverse movements unlike high strength bars that require additional restrainers to prevent shear and flexural distortion of bars. On the other hand, some of their drawbacks are they do not prevent damage due to pounding nor do they dissipate energy. In this parametric study, the existing bridge is retrofitted using cable restrainers. Since the restrainers carry tensile forces they should be provided at both ends of span in such cases. The main purpose will be to evaluate the performance of these restrainers and their impact on the seismic behavior of the superstructure.

The advantages of longitudinal joint restrainers for seismic retrofitting are:

a) Limit relative displacement at expansion joints and decrease the chances of loss of support.

b) Transfer longitudinal inertial force from superstructure to the substructure.

The requirements for restrainer are:

a) Must be strong and stiff enough to prevent joints from separating.

b) Remainder of the bridge must be able to resist the forces developed in the restrainers.

Number of restrainers are limited to prevent punching shear failures of concrete diaphragms in the expansion joints of box girders. Restrainer devices may transmit higher forces to other bridge components such as bearings and columns and may cause failure if not –properly designed.

A significant number of restrainers are sometimes required to limit joint movement to acceptable levels. In some cases it is physically impossible to include required number of restrainers. However, in other cases large number of restrainers could severely overstress components elsewhere in the bridge. So the main dilemma is to whether to increase the number of restrainers to prevent unseating or to protect structural components from induced restrainer forces. Restrainers thus may or may not be a good retrofitting solution and other alternatives such as seat extenders, isolation bearings, etc. can be used. The location of the cable restrainers, connecting the superstructure to the bent cap is shown in Fig.5-2.

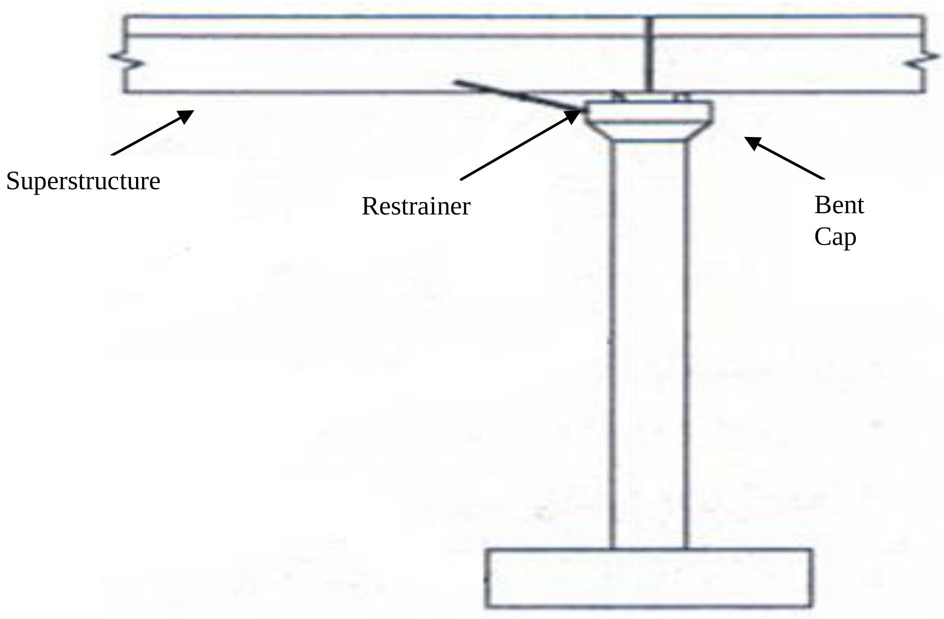

Figure 5-2: Location of restrainer showing connection between the superstructure and the bent cap [15]

The design steps for the restrainer are based on MCEER guidelines [15] and the steps are:

1) Find the maximum allowable expansion joint displacement: to find this we find the maximum permissible restrainer elongation D_r, by using this equation:

$$D_r = D_y + D_{rs} \tag{5.1}$$

where, D_y is the restrainer elongation at yield, i.e. $D_y = f_y$ Lr/E, where L_r is the length of the restrainer, and f_y is the yield stress of restrainer and E is modulus of elasticity of it. D_{rs} is the clearance provided for thermal expansion and is called restrainer slack. Now if the value of D_r is greater than 67% of available seat width D_{as}, then expansion joint can be unseated even when the maximum deformation capacity of restrainer has not been utilized. In such case we either reduce D_r or increase D_{as}. In our analysis we are using 19 mm diameter steel cable restrainers.

2) Then we find the unrestrained relative expansion of joint, D_{eq},(from analysis of model) and if it's less than 0.67 times available seat width D_{as}, then no restrainers are required, else we require restrainers.

3) Then we estimate the initial number of restrainers required, N_r, say to be 4 for first trial, and find out the initial stiffness of restrainer K_r,

$$K_r= (N_r*f_y*A_r)/ D_r \tag{5.2}$$

In our case, length of restrainer is calculated as per model geometry, and then the initial stiffness of restrainer is found out.

4) Use this value of K_r as a link element connecting deck to bent cap, and run the analysis.

5) If the analysis results give that $D_{eq} > 0.67\ D_{as}$, then repeat the procedure by increasing number of restrainers, and stop when $D_{eq} < 0.67\ D_{as}$.

In this study, based on above procedure ten number of 19mm dia. cable restrainers are used to connect deck to the bent cap.

The restrainer element is modeled as a linear elastic element having stiffness in longitudinal and transverse direction. The effective stiffness of the link element is 171.50 kip/in (30 kN/mm), and number of restrainers is ten. In the model, all the restrainer elements are combined to give one link element which links the deck to the bent cap, its effective stiffness is 1715.01 kip/in (300 kN/mm). Restrainers are designed to resist the maximum calculated force within their elastic range. They are positioned in a symmetric way to prevent eccentric movement of the joint. Adequate gap is provided to prevent in-service movements.

5.4.1. Modal characteristics of the bridge

According to Table 5-54, the structural period for NCS-R models is lower than NCS models due to large increment in stiffness of the substructure when restrainers are added. As such, the structure becomes increasing stiff due to the addition of the restrainers, which results in a lower time period. The fundamental mode of vibration is also transverse and the second mode is longitudinal for all the models having restrainers.

Table 5-54: Structural period of first four modes (NCS-R models)

Mode	Time Period (s)		
	NCS P1-1, 1-2-R	NCS P2-1, 3-1-R	NCS P2-2, 3-2-R
1	0.57	0.56	0.60
2	0.32	0.32	0.32
3	0.19	0.19	0.19
4	0.19	0.18	0.18

5.4.2. Maximum displacement of pedestals

According to Tables 5-55-5-57, compared to the behavior of NCS models the ‘C/D’ ratios have shown a significant improvement in longitudinal direction. In fact, the retrofitted bridge can perform satisfactorily for moderate intensity earthquakes, although the ‘C/D’ ratios have improved for high intensity earthquakes but it is still below one and is unsafe. But in transverse direction, the ‘C/D’ ratios have decreased as no restrainers are located in the transverse direction. As such, there is greater difference in stiffness in longitudinal direction and transverse direction, and the pedestals tend to displace more in the direction of less stiffness.

Table 5-55: Maximum displacement of pedestals NCS P1-1, 1-2-R

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	0.39	0.85	0.79	1.22	0.75	4.15	56.27	19.89
Lowndes475	Min	-0.28	-0.93	-0.76	-1.33	-0.73	-5.97	58.49	13.83
Lowndes2475	Max	0.91	1.93	2.91	2.72	2.93	10.01	15.17	8.25
Lowndes2475	Min	-1.03	-1.97	-3.11	-2.79	-3.01	-13.37	14.29	6.17
Liberty475	Max	0.82	1.83	2.66	2.62	2.83	9.39	15.71	8.79
Liberty475	Min	-0.91	-1.95	-2.53	-2.74	-2.7	-12.35	16.46	6.68
Bartow475	Max	1.1	2.17	3.65	3.11	3.57	12.39	12.18	6.66
Bartow475	Min	-1.13	-2.45	-3.39	-3.62	-3.51	-15.78	12.66	5.23
Fortpayne475	Max	1.08	1.56	2.26	1.92	2.33	6.17	19.08	13.38
Fortpayne475	Min	-0.62	-1.42	-2.03	-1.83	-2.2	-7.59	20.20	10.88
Bartow2475	Max	3.41	2.44	10.13	3.62	10.13	15.49	4.39	5.33
Bartow2475	Min	-3.25	-2.98	-10.38	-4.35	-10.57	-18.99	4.21	4.35
Charleston475	Max	5.26	5.28	15.46	7.62	14.57	30.86	2.88	2.67
Charleston475	Min	-4.95	-6.88	-16.06	-9.51	-14.9	-30.78	2.77	2.68
Moderate Intensity Earthquakes									
Liberty2475	Max	5.3	11.01	16.95	16.28	16.01	70.43	2.62	1.17
Liberty2475	Min	-5.3	-8.76	-17.28	-12.67	-17.26	-49.24	2.57	1.68
El Centro	Max	5.46	8.57	16.23	12.47	17.3	53.64	2.57	1.54
El Centro	Min	-6.54	-8.42	-19.02	-11.45	-18.42	-42.21	2.34	1.96
Fortpayne2475	Max	3.92	4.57	9.31	5.57	9.4	22.15	4.73	3.73
Fortpayne2475	Min	-3.56	-5	-9.98	-5.82	-9.78	-18.87	4.45	4.37
High Intensity Earthquakes									
Northridge	Max	15.79	14.67	49.7	20.91	53.65	78.45	**0.83**	1.05
Northridge	Min	-19.32	-22.23	-69.4	-33.5	-78.91	-97.47	**0.56**	**0.85**
Charleston2475	Max	7.81	53.21	32.62	78.62	49.33	306.49	**0.90**	**0.27**
Charleston2475	Min	-16.14	-27.5	-55.91	-38.4	-55.22	-137.06	**0.80**	**0.60**

Table 5-56: Maximum displacement of pedestals NCS P2-1, 3-1-R

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	0.31	0.72	0.82	0.97	0.74	3.17	43.37	16.03
Lowndes475	Min	-0.22	-0.67	-0.62	-0.91	-0.78	-3.42	45.59	14.85
Lowndes2475	Max	1.04	1.97	3.25	2.71	3.09	10.01	10.94	5.07
Lowndes2475	Min	-1	-1.87	-3.11	-2.61	-2.94	-11.57	11.43	4.39
Liberty475	Max	1.03	1.74	2.84	2.41	2.68	8.54	12.52	5.95
Liberty475	Min	-0.88	-1.89	-2.33	-2.55	-2.37	-9.44	15.00	5.38
Bartow475	Max	1.14	1.73	3.51	2.35	3.65	8.94	9.74	5.68
Bartow475	Min	-1.09	-1.89	-3.41	-2.64	-3.54	-9.85	10.05	5.16
Fortpayne475	Max	0.91	1.48	2.17	1.87	2.28	5.55	15.60	9.15
Fortpayne475	Min	-0.58	-1.26	-1.98	-1.67	-2.12	-4.9	16.77	10.37
Bartow2475	Max	3.2	2.54	9.96	3.35	9.75	14.55	3.57	3.49
Bartow2475	Min	-3.04	-2.22	-9.99	-3.18	-10.44	-12.54	3.41	4.05
Charleston475	Max	4.47	4.91	15.05	6.97	14.71	23.18	2.36	2.19
Charleston475	Min	-4.83	-6.25	-14.89	-8.47	-13.4	-27.66	2.39	1.84
Moderate Intensity Earthquakes									
Liberty2475	Max	5.39	8.28	17.49	12.46	16.52	50.26	2.03	1.01
Liberty2475	Min	-5.19	-7.45	-17.35	-10.29	-17.76	-40.71	2.00	1.25
El Centro	Max	6.59	5.9	18.91	8.69	17.17	32.17	1.88	1.58
Fortpayne2475	Max	3.75	4.83	9.09	5.94	9.05	21.94	3.91	2.32
Fortpayne2475	Min	-3.22	-4.15	-9.66	-4.98	-10.44	-14.96	3.41	3.40
Liberty2475	Max	5.39	8.28	17.49	12.46	16.52	50.26	2.03	1.01
High Intensity Earthquakes									
Charleston2475	Max	11.12	53.57	41.94	77.94	50.12	282.38	**0.71**	**0.18**
Charleston2475	Min	-11.88	-36.46	-47.01	-52.12	-53.23	-191.18	**0.67**	**0.27**
Charleston2475	Max	11.12	53.57	41.94	77.94	50.12	282.38	**0.71**	**0.18**
Charleston2475	Min	-11.88	-36.46	-47.01	-52.12	-53.23	-191.18	**0.67**	**0.27**

Table 5-57: Maximum displacement of pedestals NCS P2-2, 3-2-R

Ground Motion	Type	BTJ-2a		BTJ-2b		BTJ-4		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	X	Y
Low Intensity Earthquakes									
Lowndes475	Max	0.22	0.31	0.8	0.42	0.86	0.7	103.36	72.57
Lowndes475	Min	-0.13	-0.38	-0.61	-0.53	-0.73	-1.04	121.77	48.85
Lowndes2475	Max	0.9	1.28	3.04	1.74	3.13	5.14	28.40	9.88
Lowndes2475	Min	-0.77	-0.95	-2.9	-1.38	-3.14	-5.5	28.31	9.24
Liberty475	Max	0.75	0.94	2.66	1.24	2.79	3.32	31.86	15.30
Liberty475	Min	-0.71	-1.02	-2.2	-1.22	-2.36	-3.93	37.67	12.93
Bartow475	Max	1.13	1.01	3.74	1.41	3.78	4.12	23.52	12.33
Bartow475	Min	-0.95	-1.16	-3.29	-1.51	-3.53	-4.07	25.18	12.48
Fortpayne475	Max	0.78	0.75	2.03	0.86	2.07	1.33	42.94	38.20
Fortpayne475	Min	-0.48	-0.92	-2.04	-1.15	-2.27	-2.69	39.16	18.88
Bartow2475	Max	3.12	1.96	10.02	2.76	9.87	10.75	8.87	4.73
Bartow2475	Min	-2.96	-1.89	-9.67	-2.71	-9.91	-12.07	8.97	4.21
Charleston475	Max	4.86	3.29	14.9	4.74	14.6	17.34	5.97	2.93
Charleston475	Min	-4.48	-3.98	-14.02	-5.57	-13.62	-22.66	6.34	2.24
Moderate Intensity Earthquakes									
Liberty2475	Max	5.36	7.99	17.09	11.87	16.61	54.39	5.20	**0.93**
Liberty2475	Min	-4.97	-6.68	-17.1	-9.34	-17.61	-38.3	5.05	1.33
El Centro	Max	5.66	6.85	16.81	9.96	16.76	41.31	5.29	1.23
El Centro	Min	-5.66	-6.16	-17.47	-8.49	-17.22	-34.1	5.09	1.49
Fortpayne2475	Max	3.62	3.83	8.75	4.7	9.01	16.74	9.87	3.03
Fortpayne2475	Min	-3.02	-2.82	-9.85	-3.44	-10.4	-9.65	8.55	5.26
High Intensity Earthquakes									
Northridge	Max	15.24	7.35	49.03	11.1	50.9	64.45	1.75	**0.79**
Northridge	Min	-18.44	-20.67	-62.91	-30.74	-73.66	-103.36	1.21	**0.49**
Charleston2475	Max	11.76	68.41	36.13	99.45	49.65	410.04	1.79	**0.12**
Charleston2475	Min	-12.88	-44.33	-46.97	-65.51	-52.66	-273.81	1.69	**0.19**

5.4.3. Maximum force transmitted to pedestals

According to Tables 5-58-5-60, the force transmitted to the pedestals has decreased substantially when compared to the response of the NCS models in transverse direction as it is relatively less stiff. But in longitudinal direction due to high stiffness, large force is transmitted to pedestals.

5.4.4. Maximum sliding of pedestals

The ‘C/D’ ratios are having safe values for all the cases as indicated in Tables 5-61-5-63. Similar to the NCS models, sliding seems to not be of much concern provided adequate seat width (W) is available.

5.4.5. Pounding analysis of the superstructure

According to Tables 5-64-5-66, the ‘C/D’ ratios for pounding analysis of the superstructure have increased considerable when compared to response of the NCS models. Even for high intensity earthquakes the pounding force transmitted to the adjacent superstructure is relatively lower.

Table 5-58: Maximum force transmitted to pedestals NCS P1-1, 1-2-R

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	1.02	0.19	1.18	0.75	3.62	13.01	95.88	9.63
Lowndes475	Min	-0.3	-0.04	-0.4	-0.14	-0.74	-3.63	578.92	80.43
Lowndes2475	Max	4.25	0.54	4.98	1.67	12.86	25.36	26.99	4.94
Lowndes2475	Min	-1.34	-0.09	-1.52	-0.29	-3.68	-9.63	116.41	30.32
Liberty475	Max	3.74	0.54	4.26	1.64	8.84	24.67	39.26	5.08
Liberty475	Min	-1.22	-0.08	-1.36	-0.28	-2.37	-7.67	180.76	38.07
Bartow475	Max	5.19	0.52	5.46	1.97	15.58	25.98	22.28	4.82
Bartow475	Min	-1.48	-0.11	-1.9	-0.37	-4.24	-12.41	101.04	23.53
Fortpayne475	Max	3.05	0.49	3.67	1.07	9	21.51	38.56	5.83
Fortpayne475	Min	-1.08	-0.1	-1.18	-0.18	-2.79	-4.76	153.55	61.34
Bartow2475	Max	14.13	1.07	16.92	2.38	29.32	28.61	11.84	4.38
Bartow2475	Min	-4.72	-0.18	-5.22	-0.45	-14.72	-17.46	29.10	16.72
Charleston475	Max	21.12	1.74	26.53	4.64	29.63	38.21	11.71	3.28
Charleston475	Min	-7.07	-0.29	-7.79	-0.88	-20.22	-37.06	21.19	7.88
Moderate Intensity Earthquakes									
Liberty2475	Max	23.48	2.04	28.03	10.43	30	93.75	11.57	1.34
Liberty2475	Min	-7.72	-0.4	-8.77	-1.31	-22.89	-133.61	18.72	2.19
El Centro	Max	25.36	2.27	28.15	8.13	31.3	68.36	11.09	1.83
El Centro	Min	-8.11	-0.38	-8.58	-1.13	-27.28	-103.05	15.70	2.83
Fortpayne2475	Max	13.41	2.14	17.02	3.24	28.71	33.2	12.09	3.77
Fortpayne2475	Min	-4.7	-0.35	-4.9	-0.5	-11.71	-21.14	36.58	13.81
High Intensity Earthquakes									
Northridge	Max	30.76	10.21	34.61	12.83	49.31	106.72	7.04	1.17
Northridge	Min	-42.95	-1.4	-44.69	-3.27	-92.2	-358.15	4.65	**0.82**
Charleston2475	Max	30.04	7.79	32.57	27.74	33.7	389.87	10.30	**0.32**
Charleston2475	Min	-33.43	-1.93	-32.92	-3.78	-53.32	-660.94	8.03	**0.44**

Table 5-59: Maximum force transmitted to pedestals NCS P2-1, 3-1-R

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	6.05	0.14	5.98	0.32	6.58	7.12	35.79	22.97
Lowndes475	Min	-0.02	-1.32	-0.05	-4.56	-0.12	-13.09	1703.50	10.39
Lowndes2475	Max	7.93	0.31	8.28	0.9	11.19	20.13	21.05	8.12
Lowndes2475	Min	-0.03	-4.41	-0.02	-10.51	-0.16	-23.26	1277.63	5.85
Liberty475	Max	7.7	0.28	7.63	0.85	10.42	18.22	22.60	8.98
Liberty475	Min	-0.04	-3.67	-0.02	-10.49	-0.11	-20.25	1858.36	6.72
Bartow475	Max	8.21	0.31	8.54	0.87	12.84	19.06	18.34	8.58
Bartow475	Min	-0.02	-4.35	-0.03	-10.51	-0.23	-20.3	888.78	6.70
Fortpayne475	Max	7.11	0.26	7.37	0.6	10.32	12.42	22.82	13.17
Fortpayne475	Min	-0.04	-3.79	-0.03	-7.62	-0.16	-15.32	1277.63	8.88
Bartow2475	Max	11	0.69	11.78	1.23	23.4	28.04	10.07	5.83
Bartow2475	Min	-0.02	-8.68	-0.01	-10.62	-13.85	-25.16	14.76	5.41
Charleston475	Max	12.88	1.3	13.48	2.7	33.69	57.02	6.99	2.87
Charleston475	Min	-0.01	-10.52	-0.03	-11.45	-22	-57.21	9.29	2.38
Moderate Intensity Earthquakes									
Liberty2475	Max	13.47	1.44	14.73	5.58	27.26	100.82	8.64	1.62
Liberty2475	Min	-0.01	-10.66	-0.04	-11.92	-21.6	-83.5	9.46	1.63
El Centro	Max	13.51	1.36	15.31	4.23	34.06	83.21	6.92	1.97
El Centro	Min	-0.02	-10.55	-0.06	-11.77	-26.21	-76.18	7.80	1.79
Fortpayne2475	Max	10.94	1.16	11.61	2.13	23.31	50.72	10.10	3.22
Fortpayne2475	Min	-0.03	-10.66	-0.02	-10.83	-15	-29.4	13.63	4.63
High Intensity Earthquakes									
Northridge	Max	34.54	5.74	62.23	8.17	98.54	132.1	2.39	1.24
Northridge	Min	-36.34	-11.62	-41.66	-15.53	-89.15	-178.02	2.29	**0.76**
Charleston2475	Max	30.99	6.88	43.03	24.05	52.15	516.44	4.52	**0.32**
Charleston2475	Min	-27.11	-13.24	-28.02	-19.57	-56.22	-352.87	3.64	**0.39**

Table 5-60: Maximum force transmitted to pedestals NCS P2-2, 3-2-R

Ground Motion	Type	B-2a		B-2b		B-4		Max. 'C/D' ratio	
		Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Shear (y-y)	Shear (x-x)	Y-Y	X-X
Low Intensity Earthquakes									
Lowndes475	Max	4.83	0.71	4.78	1.07	4.04	5.05	50.97	48.05
Lowndes475	Min	0	-2.2	0	-6.01	0	-12.02	------	22.66
Lowndes2475	Max	6.53	1.92	6.82	4.81	9.22	16.19	26.70	14.99
Lowndes2475	Min	0	-6.54	0	-12.04	-0.01	-16.62	------	16.39
Liberty475	Max	6.4	1.86	6.13	3.15	8.03	14.96	30.66	16.22
Liberty475	Min	0	-5.39	0	-11.84	0	-14.88	------	18.31
Bartow475	Max	7	1.94	7.12	4.08	11.42	15.3	21.56	15.86
Bartow475	Min	0	-7.51	0	-12.02	0	-15.31	------	17.79
Fortpayne475	Max	5.72	2.75	6.13	2.35	7.3	12.79	33.73	18.97
Fortpayne475	Min	0	-9.23	0	-11.96	0	-12.87	------	21.17
Bartow2475	Max	11.75	5.37	13.04	10.08	28.33	22.97	8.69	10.56
Bartow2475	Min	0	-12.05	0	-12.22	-6.4	-24.94	37.08	10.92
Charleston475	Max	16.22	9.38	17.47	12.39	36.94	28.41	6.66	8.54
Charleston475	Min	0	-12.11	0	-12.41	-11.77	-33.16	20.16	8.22
Moderate Intensity Earthquakes									
Liberty2475	Max	17.7	9.62	21.04	14.27	36.2	51.04	6.80	4.75
Liberty2475	Min	0	-12.22	-1.6	-12.6	-14.58	-44.85	16.28	6.07
El Centro	Max	18.07	11.26	20.78	13.87	36.3	40.23	6.78	6.03
El Centro	Min	-0.47	-12.23	-1.52	-12.77	-12.82	-39.43	18.51	6.91
Fortpayne2475	Max	11.49	11.55	13.52	11.98	21.59	27.55	11.40	8.81
Fortpayne2475	Min	0	-12.25	0	-12.29	-5.33	-24.64	44.52	11.06
High Intensity Earthquakes									
Northridge	Max	49.57	14.64	73.1	14.38	106.12	81	2.32	3.00
Northridge	Min	-31.14	-12.74	-35.43	-16.9	-102.25	-136.5	2.32	2.00
Charleston2475	Max	40.22	14.72	56.86	27.29	59.34	240.22	4.15	1.01
Charleston2475	Min	-20.38	-14.47	-18.55	-27.24	-43.27	-447.4	5.48	**0.61**

Table 5-61: Maximum sliding of pedestals NCS P1-1, 1-2-R

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	0.5	0.89	0.53	1	0.56	0.82	566.04	803.57
Lowndes475	Min	-0.48	-0.95	-0.51	-1.09	-0.46	-1.02	588.24	978.26
Lowndes2475	Max	1.74	1.99	1.9	2.24	1.38	1.83	157.89	326.09
Lowndes2475	Min	-1.92	-1.99	-2.08	-2.28	-1.69	-2.18	144.23	266.27
Liberty475	Max	1.6	1.91	1.75	2.15	1.26	1.79	171.43	357.14
Liberty475	Min	-1.5	-1.98	-1.65	-2.25	-1.59	-2.1	181.82	283.02
Bartow475	Max	2.18	2.23	2.38	2.54	1.8	2.2	126.05	250.00
Bartow475	Min	-2.08	-2.58	-2.26	-2.95	-1.97	-2.75	132.74	228.43
Fortpayne475	Max	1.47	1.48	1.56	1.62	1.39	1.13	192.31	323.74
Fortpayne475	Min	-1.14	-1.37	-1.27	-1.52	-1.42	-1.25	236.22	316.90
Bartow2475	Max	6.14	2.57	6.66	2.95	4.68	2.86	45.05	96.15
Bartow2475	Min	-6.32	-3.1	-6.88	-3.56	-5.77	-3.28	43.60	77.99
Charleston475	Max	9.49	5.62	10.29	6.32	6.62	5.83	29.15	67.98
Charleston475	Min	-9.65	-7.17	-10.53	-7.96	-9.01	-6.66	28.49	49.94
Moderate Intensity Earthquakes									
Liberty2475	Max	10.22	11.54	11.15	13.26	7.11	12.38	26.91	63.29
Liberty2475	Min	-10.47	-9.07	-11.42	-10.33	-9.46	-8.94	26.27	47.57
El Centro	Max	10	8.83	10.85	10.14	9.46	9.75	27.65	47.57
El Centro	Min	-11.82	-8.37	-12.81	-9.4	-11.49	-7.09	23.42	39.16
Fortpayne2475	Max	5.89	4.35	6.29	4.72	5.37	3.85	47.69	83.80
Fortpayne2475	Min	-6.09	-4.6	-6.59	-4.92	-5.65	-3.43	45.52	79.65
High Intensity Earthquakes									
Northridge	Max	30.22	15.49	32.91	17.41	30.58	17.47	9.12	14.72
Northridge	Min	-41.51	-25.19	-45.45	-28	-45.11	-25.46	6.60	9.98
Charleston2475	Max	18.93	56.74	20.91	64.49	37.32	58.95	14.35	12.06
Charleston2475	Min	-33.41	-28.76	-36.56	-31.88	-32.98	-27.84	8.21	13.64

Table 5-62: Maximum sliding of pedestals NCS P2-1, 3-1-R

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	0.49	0.73	0.58	0.81	0.47	0.68	517.24	957.45
Lowndes475	Min	-0.38	-0.68	-0.45	-0.75	-0.71	-0.75	666.67	633.80
Lowndes2475	Max	1.87	2	2.24	2.25	1.44	1.97	133.93	312.50
Lowndes2475	Min	-1.81	-1.9	-2.17	-2.15	-1.82	-2.11	138.25	247.25
Liberty475	Max	1.69	1.78	2	2	1.37	1.75	150.00	328.47
Liberty475	Min	-1.38	-1.86	-1.61	-2.11	-1.7	-1.84	186.34	264.71
Bartow475	Max	2.03	1.74	2.43	1.95	1.93	1.73	123.46	233.16
Bartow475	Min	-2	-1.93	-2.39	-2.19	-2.31	-2.05	125.52	194.81
Fortpayne475	Max	1.28	1.42	1.52	1.57	1.04	1.17	197.37	432.69
Fortpayne475	Min	-1.11	-1.25	-1.35	-1.38	-1.66	-0.99	222.22	271.08
Bartow2475	Max	5.74	2.5	6.89	2.79	5.39	2.54	43.54	83.49
Bartow2475	Min	-5.62	-2.3	-6.83	-2.62	-5.87	-2.61	43.92	76.66
Charleston475	Max	8.46	5.2	10.28	5.83	7.61	5.24	29.18	59.13
Charleston475	Min	-8.55	-6.43	-10.28	-7.13	-8.15	-6.09	29.18	55.21
Moderate Intensity Earthquakes									
Liberty2475	Max	10.01	8.85	12.06	10.17	8.58	10.1	24.88	52.45
Liberty2475	Min	-9.91	-7.58	-11.98	-8.54	-10.36	-7.91	25.04	43.44
El Centro	Max	11.16	6.25	13.26	7.13	9.25	6.75	22.62	48.65
El Centro	Min	-10.94	-6.17	-13.14	-7.12	-11.94	-6.87	22.83	37.69
Fortpayne2475	Max	5.66	4.61	6.55	5.04	5.03	3.96	45.80	89.46
Fortpayne2475	Min	-5.66	-3.91	-6.75	-4.23	-6.41	-2.73	44.44	70.20
High Intensity Earthquakes									
Northridge	Max	29.62	8.56	35.52	10.01	30.9	10.41	8.45	14.56
Northridge	Min	-37.2	-22.07	-45.04	-24.96	-47.71	-26.88	6.66	9.43
Charleston2475	Max	23.44	56.73	28.68	64.34	40.54	60.88	10.46	11.10
Charleston2475	Min	-26.04	-38.28	-32.02	-43.16	-35.7	-40.77	9.37	12.61

Table 5-63: Maximum sliding of pedestals NCS P2-2, 3-2-R

Ground Motion	Type	TTJ-2a		TTJ-2b		TTJ-3		Max. 'C/D' ratio	
		X	Y	X	Y	X	Y	Bent 'a'	Bent 'b'
Low Intensity Earthquakes									
Lowndes475	Max	0.47	0.33	0.52	0.35	0.54	0.2	576.92	833.33
Lowndes475	Min	-0.34	-0.4	-0.38	-0.43	-0.69	-0.29	789.47	652.17
Lowndes2475	Max	1.8	1.31	1.99	1.42	1.6	0.74	150.75	281.25
Lowndes2475	Min	-1.69	-1	-1.88	-1.1	-2.14	-0.7	159.57	210.28
Liberty475	Max	1.55	0.98	1.72	1.04	1.59	0.58	174.42	283.02
Liberty475	Min	-1.34	-0.98	-1.47	-1.02	-1.66	-0.61	204.08	271.08
Bartow475	Max	2.22	1.04	2.46	1.14	1.97	0.6	121.95	228.43
Bartow475	Min	-1.96	-1.16	-2.17	-1.26	-2.32	-0.74	138.25	193.97
Fortpayne475	Max	1.24	0.69	1.36	0.73	1.11	0.37	220.59	405.41
Fortpayne475	Min	-1.16	-0.9	-1.3	-0.96	-1.76	-0.61	230.77	255.68
Bartow2475	Max	5.99	2.02	6.61	2.23	4.96	1.41	45.39	90.73
Bartow2475	Min	-5.8	-2.07	-6.4	-2.24	-5.94	-1.76	46.88	75.76
Charleston475	Max	9.01	3.57	9.91	3.9	7.78	2.44	30.27	57.84
Charleston475	Min	-8.36	-4.23	-9.24	-4.59	-8.37	-3.25	32.47	53.76
Moderate Intensity Earthquakes									
Liberty2475	Max	10.27	8.41	11.32	9.46	8.56	5.1	26.50	52.57
Liberty2475	Min	-10.18	-6.84	-11.26	-7.55	-10.52	-4.13	26.64	42.78
El Centro	Max	10.22	7.16	11.22	7.99	9.08	4.24	26.74	49.56
El Centro	Min	-10.61	-6.14	-11.67	-6.82	-11.14	-3.71	25.71	40.39
Fortpayne2475	Max	5.6	3.62	6.04	3.92	4.95	1.9	49.67	90.91
Fortpayne2475	Min	-5.91	-2.69	-6.52	-2.87	-6.47	-1.62	46.01	69.55
High Intensity Earthquakes									
Northridge	Max	29.51	7.56	32.52	8.5	27.62	7.72	9.23	16.29
Northridge	Min	-37.93	-22.95	-41.88	-25.12	-45.79	-18.67	7.16	9.83
Charleston2475	Max	21.5	71.84	23.73	80.01	37.15	44	12.64	12.11
Charleston2475	Min	-27.67	-46.71	-30.74	-52.27	-36.03	-28.73	9.76	12.49

Table 5-64: Pounding analysis of superstructure NCS P1-1, 1-2-R

Ground Motion	Abutment (mm)	Deck joint (mm)	Axial(kN) (at abutment)	Axial(kN) (at joint)	Max. 'C/D' ratio	
					Abutment	Deck Joint
Low Intensity Earthquakes						
Lowndes475	0.28	0.52	0	0	90.71	48.85
Lowndes2475	0.98	2.19	0	0	25.92	11.60
Liberty475	0.97	1.9	0	0	26.19	13.37
Bartow475	1.07	2.34	0	0	23.74	10.85
Fortpayne475	0.67	1.71	0	0	37.91	14.85
Bartow2475	3.06	7.59	0	0	8.30	3.35
Charleston475	4.91	11.96	0	0	5.17	2.12
Moderate Intensity Earthquakes						
Liberty2475	4.87	12.46	0	0	5.22	2.04
El Centro	6.35	13.05	0	0	4.00	1.95
Fortpayne2475	3.45	7.6	0	0	7.36	3.34
High Intensity Earthquakes						
Northridge	16.21	50.94	0	5.11	1.57	**0.50**
Charleston2475	14.64	42.42	0	3.4	1.73	**0.60**

Table 5-65: Pounding analysis of superstructure NCS P2-1, 3-1-R

Ground Motion	Abutment (mm)	Deck joint (mm)	Axial(kN) (at abutment)	Axial(kN) (at joint)	Max. 'C/D' ratio	
					Abutment	Deck Joint
Low Intensity Earthquakes						
Lowndes475	0.24	0.42	0	0	105.83	60.48
Lowndes2475	0.96	2.21	0	0	26.46	11.49
Liberty475	0.91	1.74	0	0	27.91	14.60
Bartow475	1.02	2.36	0	0	24.90	10.76
Fortpayne475	0.61	1.6	0	0	41.64	15.88
Bartow2475	2.93	7.48	0	0	8.67	3.40
Charleston475	4.86	10.87	0	0	5.23	2.34
Moderate Intensity Earthquakes						
Liberty2475	4.78	12.53	0	0	5.31	2.03
El Centro	5.8	13.63	0	0	4.38	1.86
Fortpayne2475	3	6.96	0	0	8.47	3.65
High Intensity Earthquakes						
Northridge	15.9	45.95	0	4.11	1.60	**0.55**
Charleston2475	9.65	36.4	0	2.2	2.63	**0.70**

Table 5-66: Pounding analysis of superstructure NCS P2-2, 3-2-R

Ground Motion	**Abutment (mm)**	**Deck joint (mm)**	**Axial(kN) (at abutment)**	**Axial(kN) (at joint)**	**Max. 'C/D' ratio**	
					Abutment	**Deck Joint**
Low Intensity Earthquakes						
Lowndes475	0.09	0.54	0	0	282.22	47.04
Lowndes2475	0.67	2.2	0	0	37.91	11.55
Liberty475	0.69	1.69	0	0	36.81	15.03
Bartow475	0.89	2.41	0	0	28.54	10.54
Fortpayne475	0.43	1.72	0	0	59.07	14.77
Bartow2475	2.77	7.1	0	0	9.17	3.58
Charleston475	4.44	10.33	0	0	5.72	2.46
Moderate Intensity Earthquakes						
Liberty2475	4.48	12.53	0	0	5.67	2.03
El Centro	5.53	12.46	0	0	4.59	2.04
Fortpayne2475	2.72	7.32	0	0	9.34	3.47
High Intensity Earthquakes						
Northridge	15.65	44.12	0	3.74	1.62	**0.58**
Charleston2475	15.91	35.81	0	2.08	1.60	**0.71**

5.4.6. Summary of analysis results

The usage of cable restrainers for seismic retrofitting is effective way to increase the ‘C/D’ ratio and there is a considerable difference between NCS-R models and NCS models. All the NCS-R models are showing adequate ‘C/D’ ratios for moderate intensity earthquakes, and even for high intensity earthquakes the ‘C/D’ ratios are much higher than NCS models, though still unsafe. It can also be observed that since there is large increment of stiffness in longitudinal direction due to placement of restrainers, the ‘C/D’ ratios have increased in transverse direction, which is having lower stiffness. It is also observed that there is increment in the forces induced in the columns due to usage of these restrainers.

6. CONCLUSIONS AND SCOPE FOR FUTURE RESEARCH

This research is intended to model a candidate bridge in the state of Georgia supported on steel pedestals. Experimental data capturing the force-displacement hysteretic behavior provide more realistic modeling parameters of these steel pedestals, which has not been analytically explored prior to this investigation. The contribution of this research is to assess the behavior of these steel pedestals when subjected to various low-to-moderate-high types of ground motion by conducting a nonlinear time history analysis of a bridge modeled in SAP 2000. This research work is aimed to provide a new perspective on the capability of these steel pedestals to sustain seismic loads and thereby providing a guideline to the various bridge industries and DOTs extensively relying on these steel pedestals to increase the vertical clearance of the superstructure. The results from the parametric studies are analyzed to assess the performance of these steel pedestals pertaining to possible variations in critical parameters that can affect the seismic performance of the bridge such as the effect of structural mass, stiffness of expansion joint modeled using deck-gap elements, varying column height, and addition of cable restrainers on the structural response. Furthermore, the results will serve as a useful tool to check compatibility of these steel pedestals with these varying parameters as a function of a bridge's material type, geometry and applied retrofit measures.

The capacity-demand ratio ('C/D') ratio for any parameter is defined as the ratio between the capacity of the component to the actual demand of the component. The maximum force and deformation capacities of these steel pedestals are found out by experimental results [1] and are compared with the nonlinear time history analysis results of bridge models. The corresponding 'C/D' ratios for various parameters form the basis of this research.

The results for the critical earthquakes for all the models based on their average "C/D' ratio can be summarized in Tables 6-1-6-3. The plots corresponding to these results are shown in Figures 6-1 – 6-5.

Table 6-1: Average 'C/D' ratio for displacement of pedestals

Ground Motion	Model	Baseline		Light-weight deck		Heavy-weight		Stiff Deck gap		Increased column height		Retrofitted	
	Direction	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Low Intensity Earthquakes													
Charleston475		1.77	2.78	1.91	3.06	1.37	1.60	1.85	2.77	1.52	1.70	3.74	2.25
Moderate Intensity Earthquakes													
Liberty2475		0.91	1.15	0.95	1.24	0.51	0.70	0.95	1.16	0.59	0.69	3.21	1.04
El Centro		1.05	1.18	1.04	1.61	0.85	0.91	1.08	1.17	0.82	1.00	3.25	1.45
Fortpayne2475		2.65	4.79	2.82	4.98	1.78	2.63	2.74	4.73	1.77	2.88	5.01	3.39
High Intensity Earthquakes													
Northridge		0.26	0.71	0.38	0.76	0.13	0.46	0.35	0.71	0.16	0.39	0.81	0.54
Charleston2475		0.14	0.17	0.20	0.21	0.07	0.09	0.17	0.17	0.09	0.10	1.05	0.19

Table 6-2: Average 'C/D' ratio for force transmitted to pedestals

Ground Motion	Model	Baseline		Light-weight deck		Heavy-weight		Stiff Deck gap		Increased column height		Retrofitted	
	Direction	Y-Y	X-X	Y-Y	X-X	Y-Y	X-X	Y-Y	X-X	Y-Y	X-X	Y-Y	X-X
Low Intensity Earthquakes													
Charleston475		5.71	5.64	5.94	6.05	5.07	4.47	6.30	5.64	4.89	6.02	8.45	4.90
Moderate Intensity Earthquakes													
Liberty2475		2.57	2.99	2.77	3.36	2.24	1.69	2.61	3.03	2.17	2.15	9.00	2.57
El Centro		2.66	2.94	2.64	3.44	3.22	2.00	2.75	2.94	2.39	3.29	8.26	3.28
Fortpayne2475		9.64	7.93	8.94	7.92	6.69	7.26	9.75	7.91	6.29	7.89	11.20	5.27
High Intensity Earthquakes													
Northridge		1.31	1.29	1.79	1.39	0.84	0.93	1.48	1.26	0.91	0.94	3.09	1.19
Charleston2475		0.75	0.34	1.01	0.55	0.54	0.21	0.68	0.37	0.50	0.26	5.72	0.48

Table 6-3: Maximum impact force due to pounding of superstructure (kN)

Ground Motion	Baseline	Light-weight deck	Heavy-weight	Stiff Deck gap	Increased column height	Retrofitted
Charleston475	2.42	3.24	3.87	12.62	3.88	0
Liberty2475	9.35	8.14	24.03	48.85	18.25	0
El Centro	7.34	4.84	13.93	46.91	10.63	0
Fort Payne2475	0	0	1.67	0	2.28	0
Northridge	33.59	30.51	67.44	203.7	68.72	5.11
Charleston2475	122.88	104.86	157.15	689.58	144.5	3.4

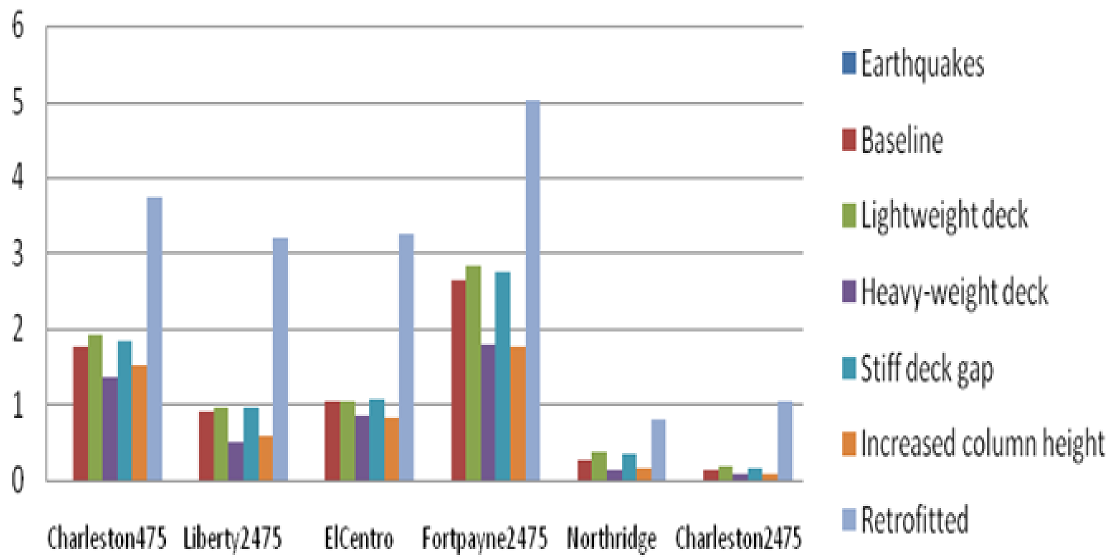

Figure 6-1: Average 'C/D' ratio for maximum pedestal displacement (longitudinal direction)

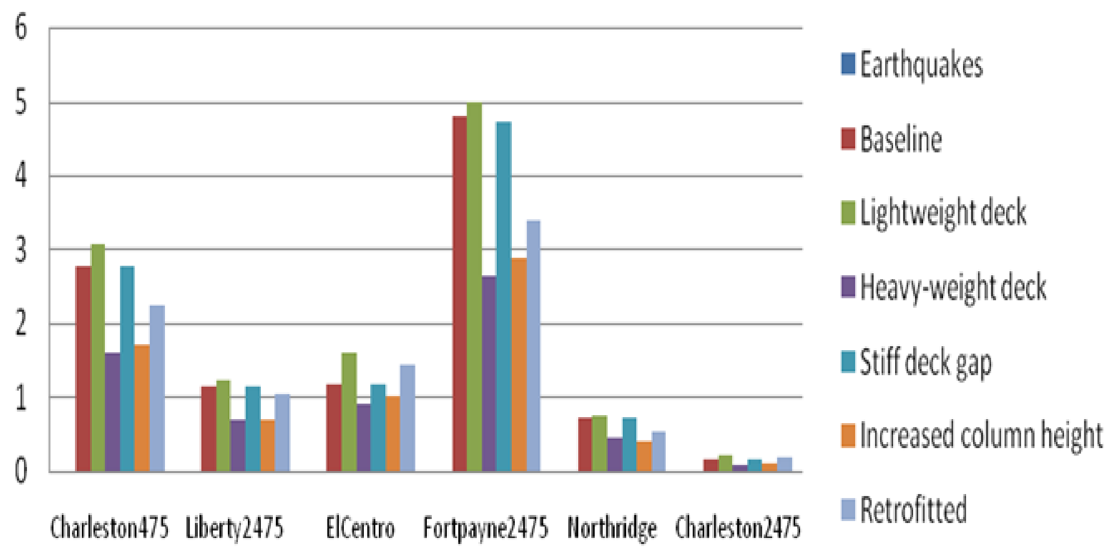

Figure 6-2: Average 'C/D' ratio for maximum pedestal displacement (transverse direction)

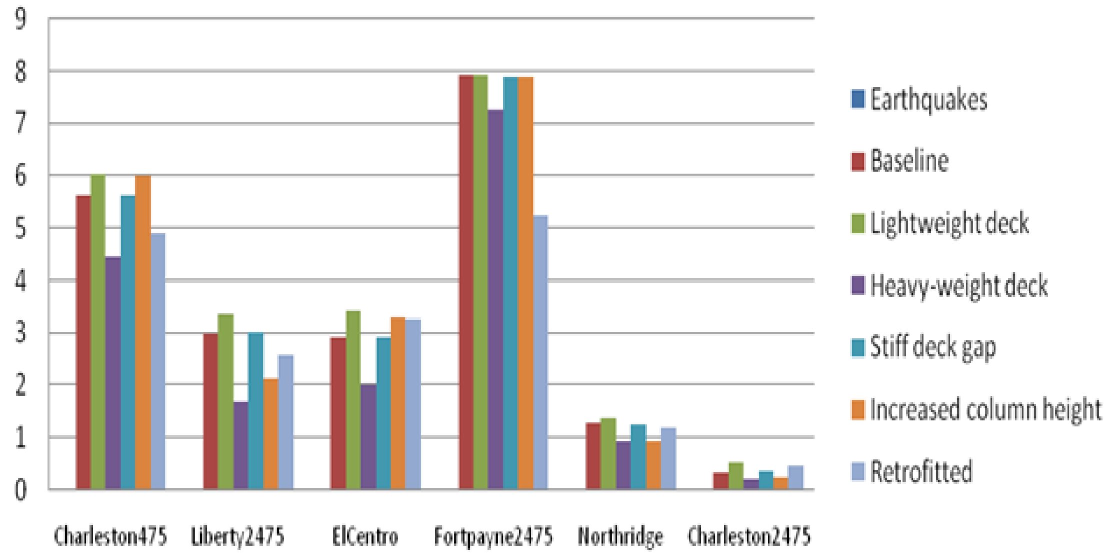

Figure 6-3: Average 'C/D' ratio for maximum force transmitted to pedestal (longitudinal direction)

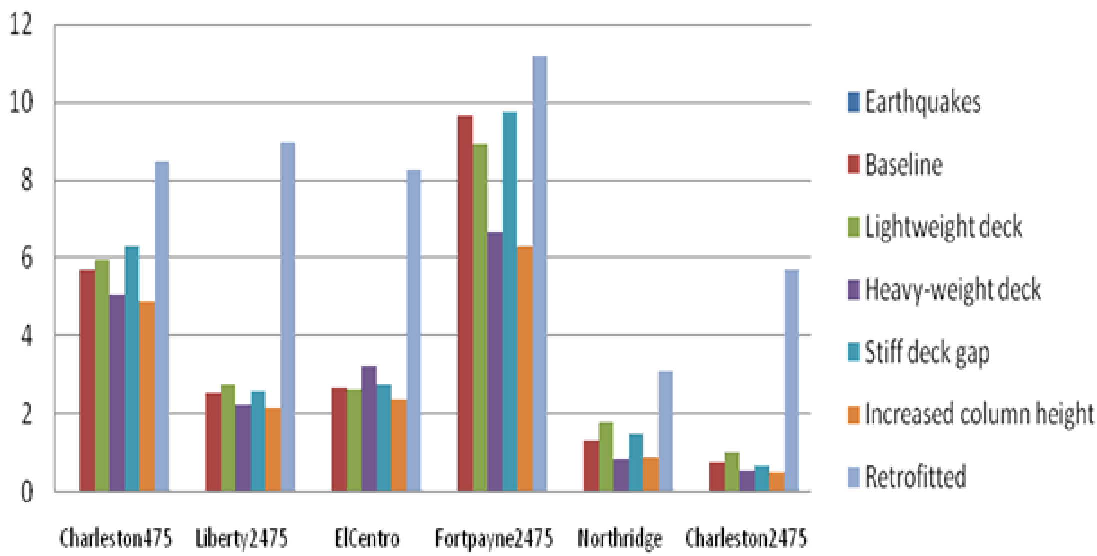

Figure 6-4: Average 'C/D' ratio for maximum force transmitted to pedestal (transverse direction)

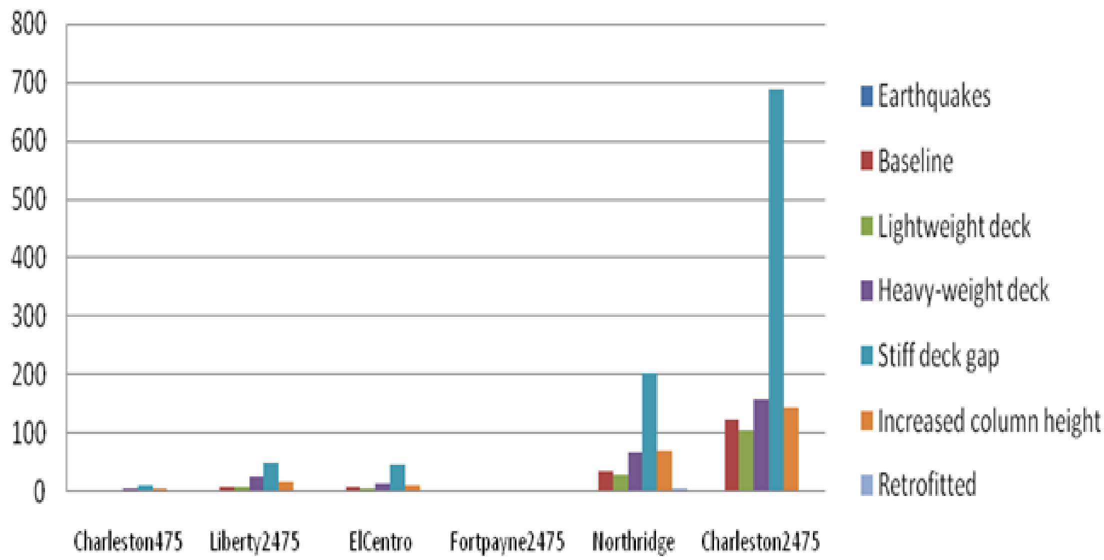

Figure 6-5: Maximum impact force transmitted to superstructure due to pounding

Based on the analysis results and the corresponding plots, we can observe some of the key points which can be observed are:

I) Conclusions based on intensity of earthquakes:

a) The performance of the steel pedestals is adequate for low seismic zones and can effectively used in those regions to increase the vertical clearance of bridges.

b) For moderate intensity earthquakes, these pedestals may require retrofitting by using cable restrainers to increase the 'C/D' ratio for adequate performance. However, if the mass of the superstructure is considerably heavy or the column heights are too high, then it is not recommended to use these pedestals.

c) The performance of these steel pedestals in high seismic zone is inadequate and should be avoided due to very low 'C/D' ratios of critical parameters.

II) Conclusions based on displacement of pedestals

a) The critical parameter is heavy mass of the superstructure followed by the height of the columns. For these two cases, the displacement of the pedestal is highest in both the longitudinal and the transverse directions.

b) The smallest pedestal displacement in the longitudinal direction is for the retrofitted model. However, the model using cable restrainers showed relatively high increments in pedestal displacements in the transverse direction. This is because there is no restrainer provided in transverse direction leading to larger displacements along the weaker axis.

c) The baseline and stiff deck gap models are showing similar pedestal displacements, so there is no change in pedestal displacement due to stiff deck gap elements.

d) The lightweight deck is having optimal pedestal displacements with the highest ‘C/D’ ratio along the transverse direction and second highest ‘C/D’ ratio in the longitudinal direction.

e) The sliding of these pedestals is not of great concern provided adequate seat width is present.

III) Conclusions based on force transmitted to pedestals

a) Larger forces are transmitted to the pedestals in the models having heavier superstructure, which is the most critical parameter followed by column height. However, this is not fixed for every earthquake and is not showing any particular trend.

b) The retrofitted model has relatively small 'C/D' ratios than other models, for the force transmitted to pedestal in the longitudinal direction but has maximum 'C/D' ratios for the force transmitted to the pedestal in the transverse direction.

c) The rest of the models show similar trends as observed from the displacements of the pedestals.

IV) Conclusions based on pounding of superstructure

a) The expansion join should not be too stiff than the adjacent bridge components to reduce chances of greater forces transmitted to the superstructure due to pounding. The relatively higher stiffness of the expansion joints is revealed to be the most critical parameter for the pounding force transmitted to the adjacent superstructure.

b) The heavier mass of superstructure and column height are other critical parameters and relatively higher pounding forces are transferred to the superstructure than the rest of the models.

c) Other models showed little or no effect of pounding and the damage due to it is not expected to be large.

Future research can be extended to include the effect of skew on the behavior of these pedestals. Also, the effect of soil-abutment interaction can also be used for more accurate modeling of foundation of columns and abutment. The effect of other seismic retrofitting like the shape memory alloys as the restrainers can also be investigated to provide a vast range for performance-based design recommendations. The effect of near-field earthquakes by inclusion of effect of vertical acceleration can also be investigated in future research.

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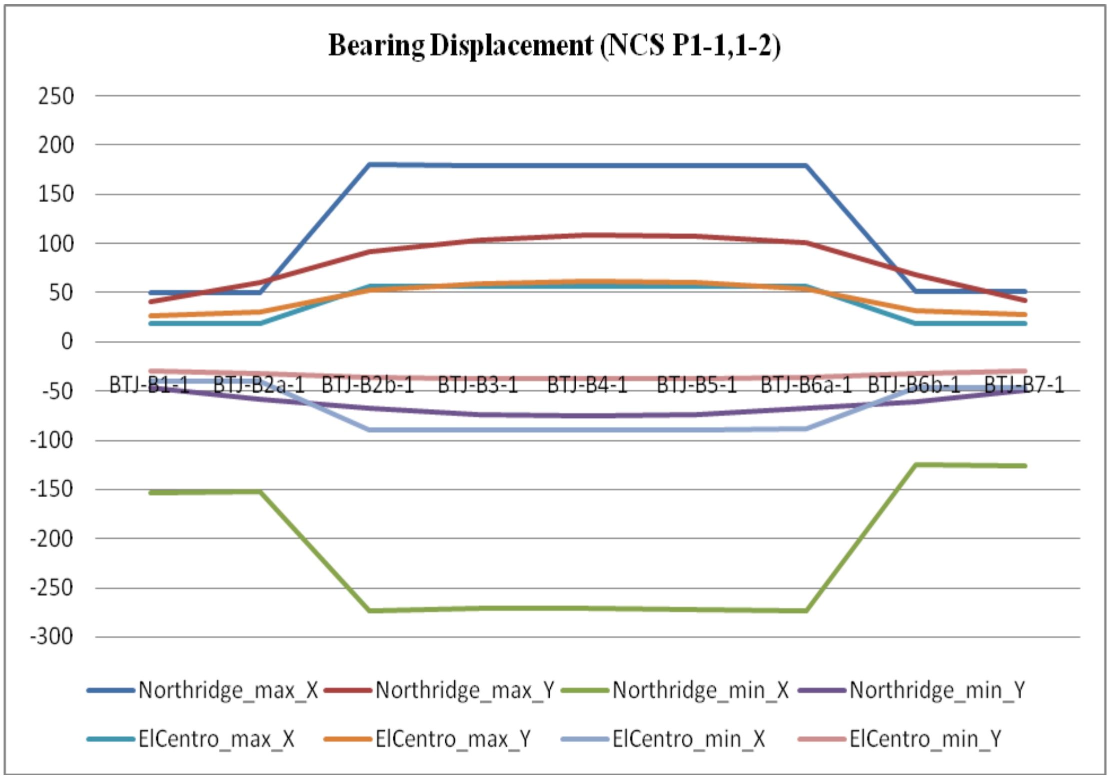
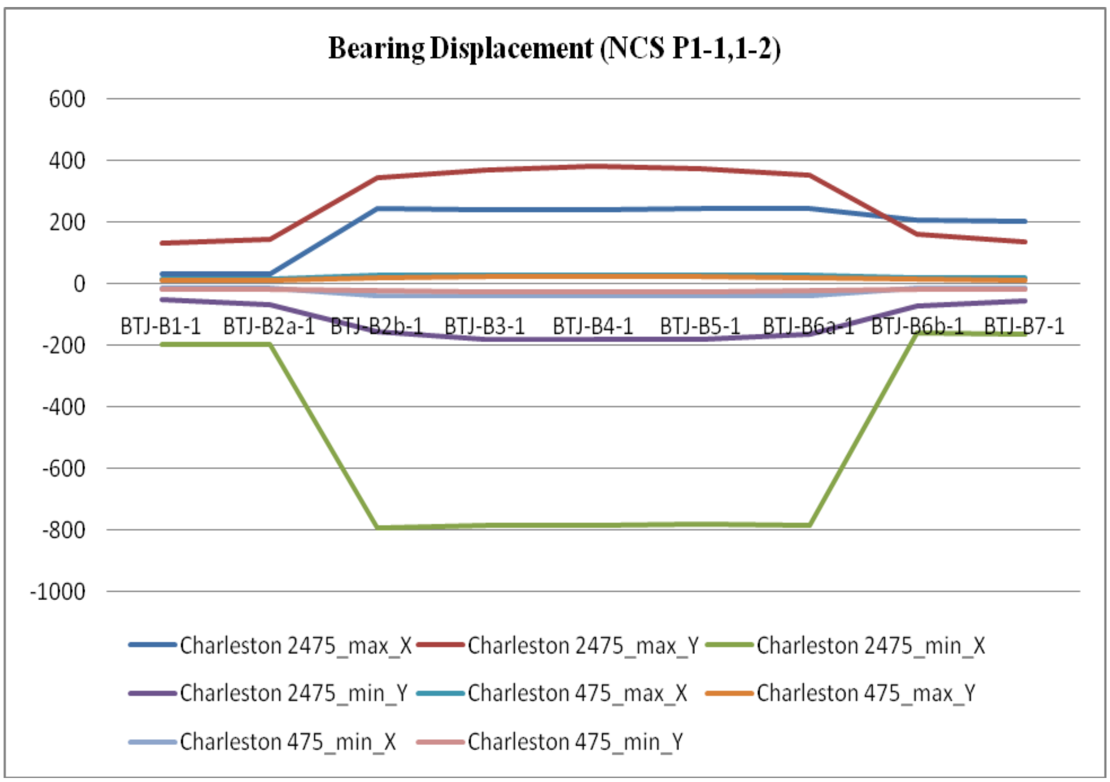
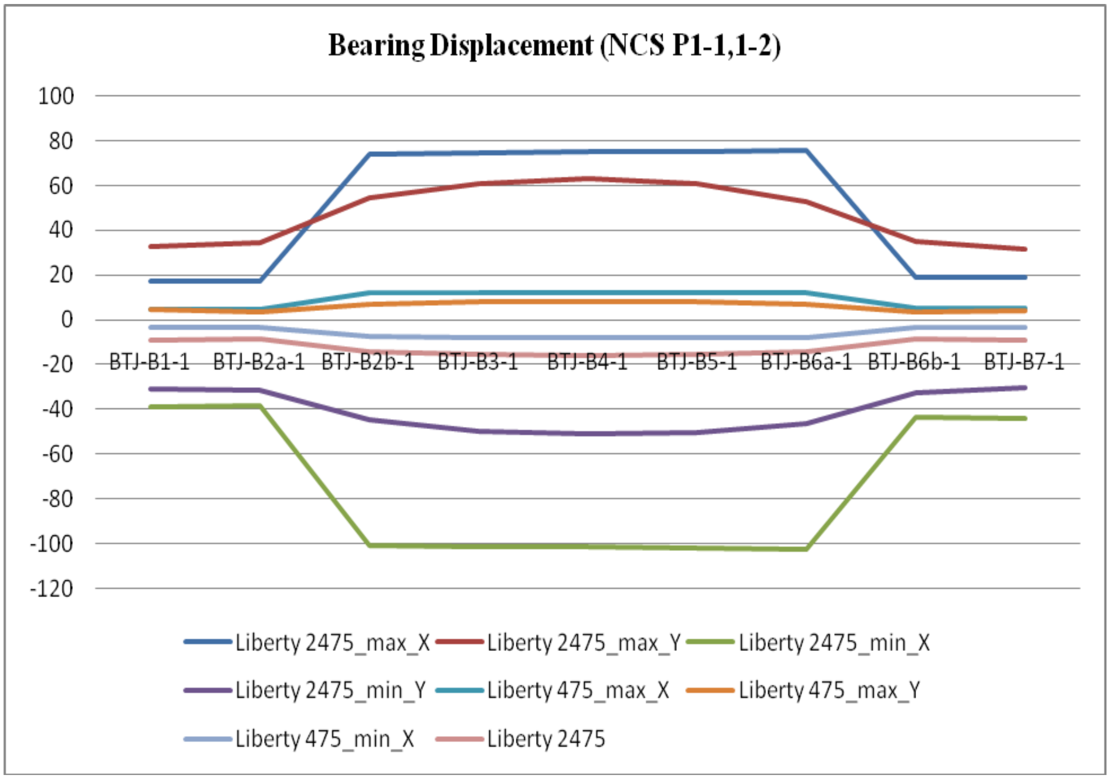
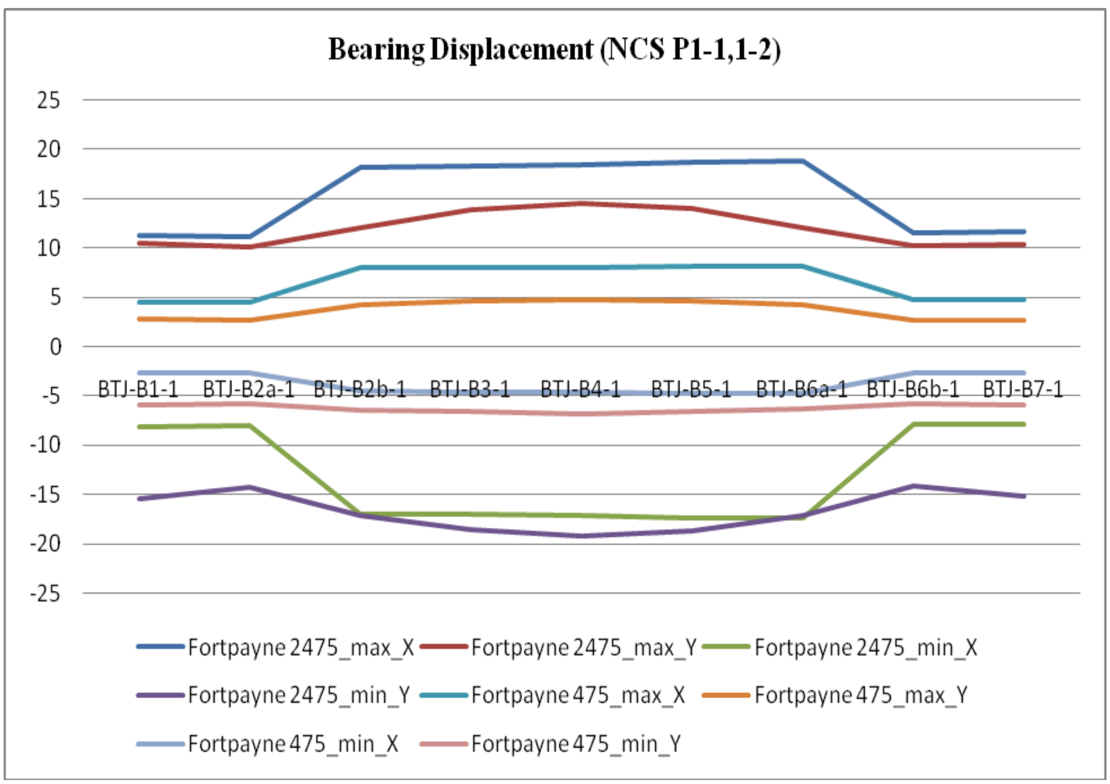
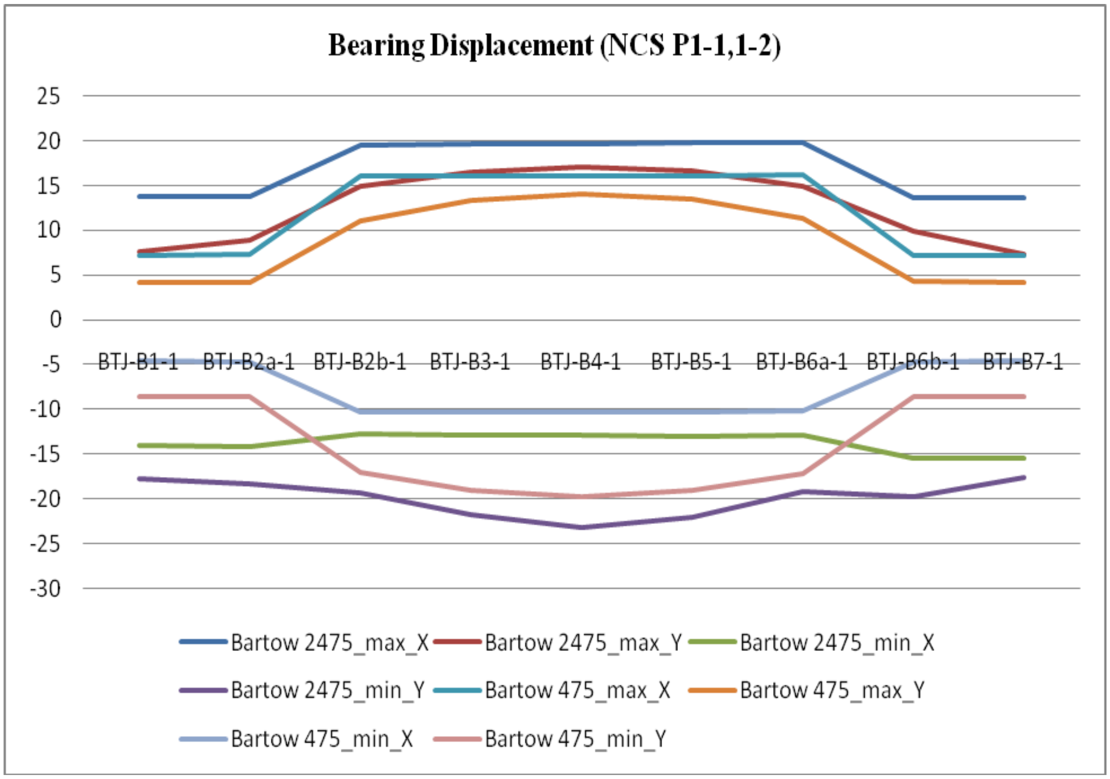
APPENDIX

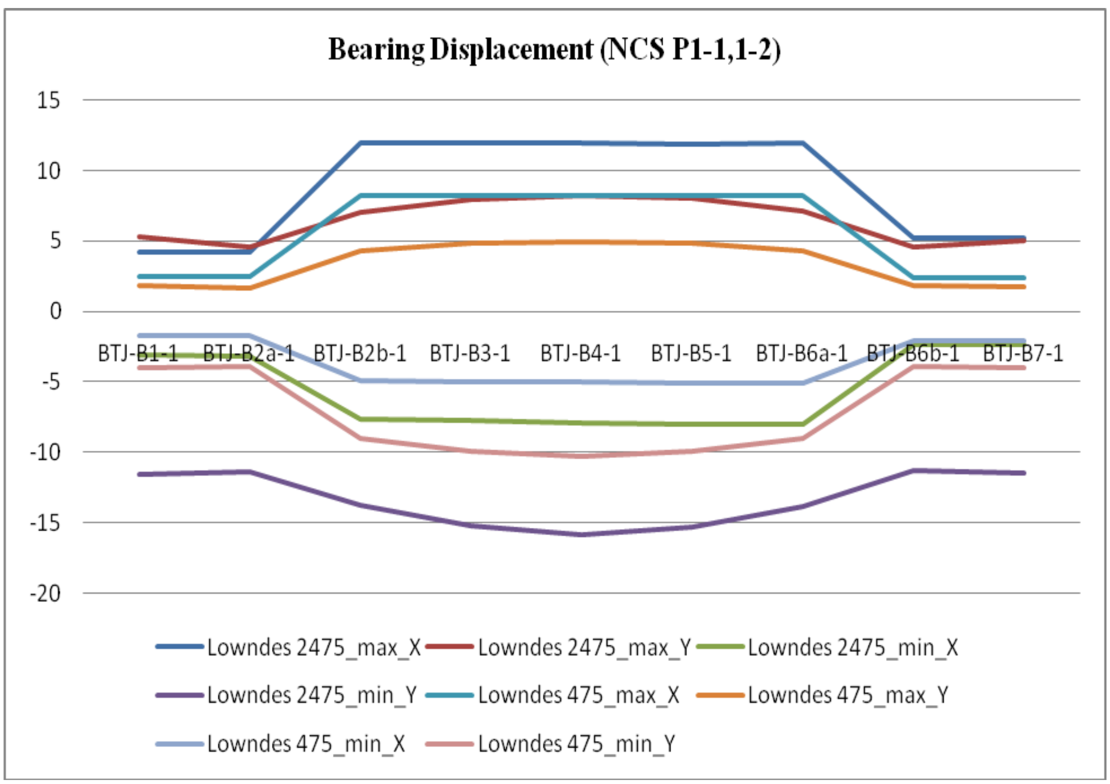

Bearing Displacement (NCS P1-1,1-2)
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Northridge_max_X
Northridge_max_Y
Northridge_min_X
Northridge_min_Y
ElCentro_max_X
ElCentro_max_Y
ElCentro_min_X
ElCentro_min_Y

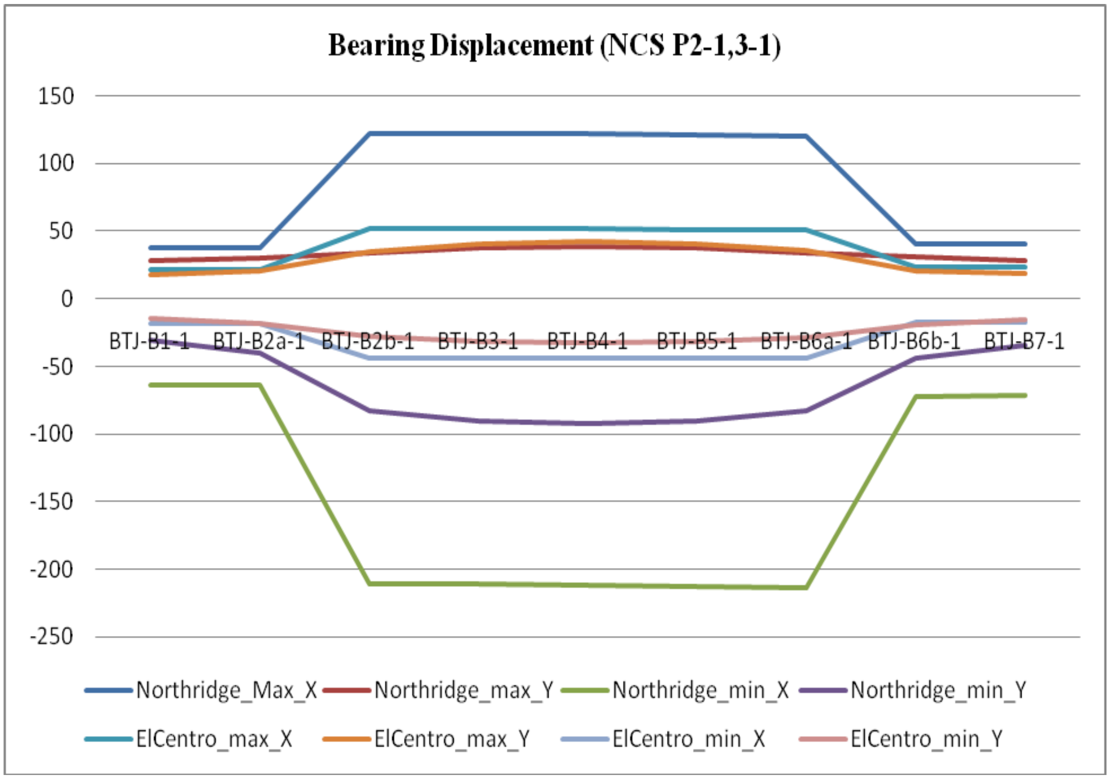

Bearing Displacement (NCS P1-1,1-2)
600
400
200
0
-200
-400
-600
-800
-1000
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Charleston 2475_max_X
Charleston 2475_max_Y
Charleston 2475_min_X
Charleston 2475_min_Y
Charleston 475_max_X
Charleston 475_max_Y
Charleston 475_min_X
Charleston 475_min_Y


Bearing Displacement (NCS P1-1,1-2)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Liberty 2475_max_X
Liberty 2475_max_Y
Liberty 2475_min_X
Liberty 2475_min_Y
Liberty 475_max_X
Liberty 475_max_Y
Liberty 475_min_X
Liberty 2475

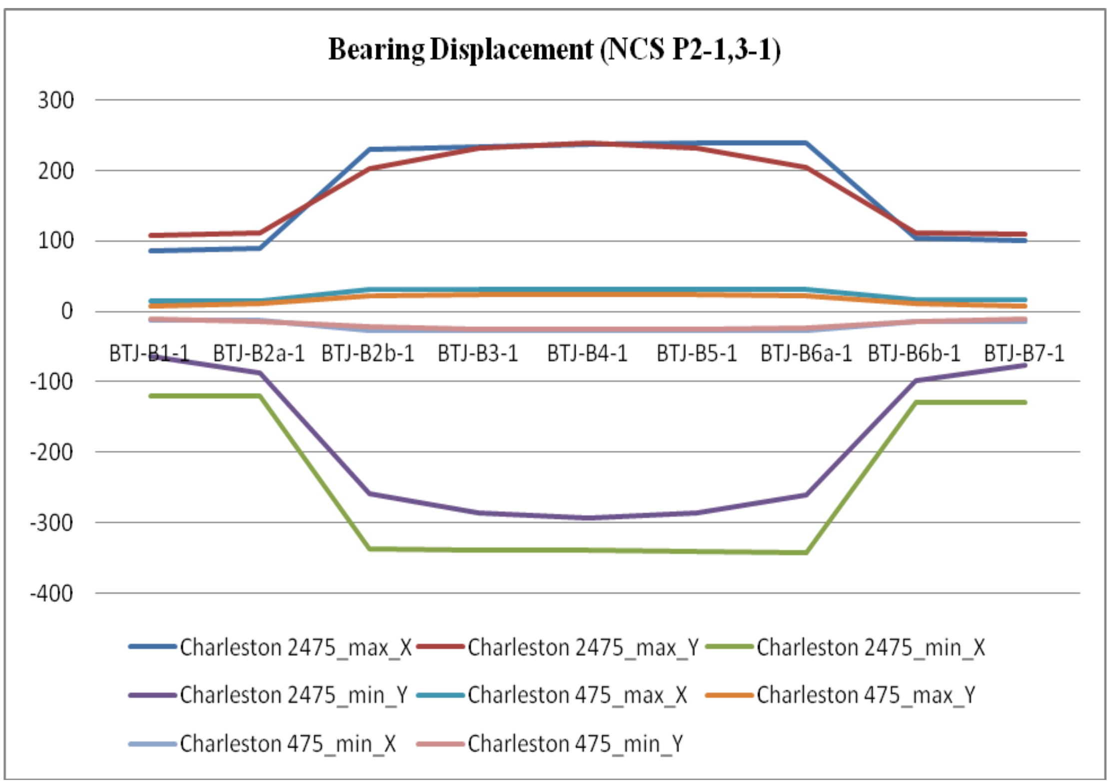

Bearing Displacement (NCS P1-1,1-2)
25
20
15
10
5
0
-5
-10
-15
-20
-25
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Fortpayne 2475_max_X
Fortpayne 2475_max_Y
Fortpayne 2475_min_X
Fortpayne 2475_min_Y
Fortpayne 475_max_X
Fortpayne 475_max_Y
Fortpayne 475_min_X
Fortpayne 475_min_Y


Bearing Displacement (NCS P1-1,1-2)
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Bartow 2475_max_X
Bartow 2475_max_Y
Bartow 2475_min_X
Bartow 2475_min_Y
Bartow 475_max_X
Bartow 475_max_Y
Bartow 475_min_X
Bartow 475_min_Y

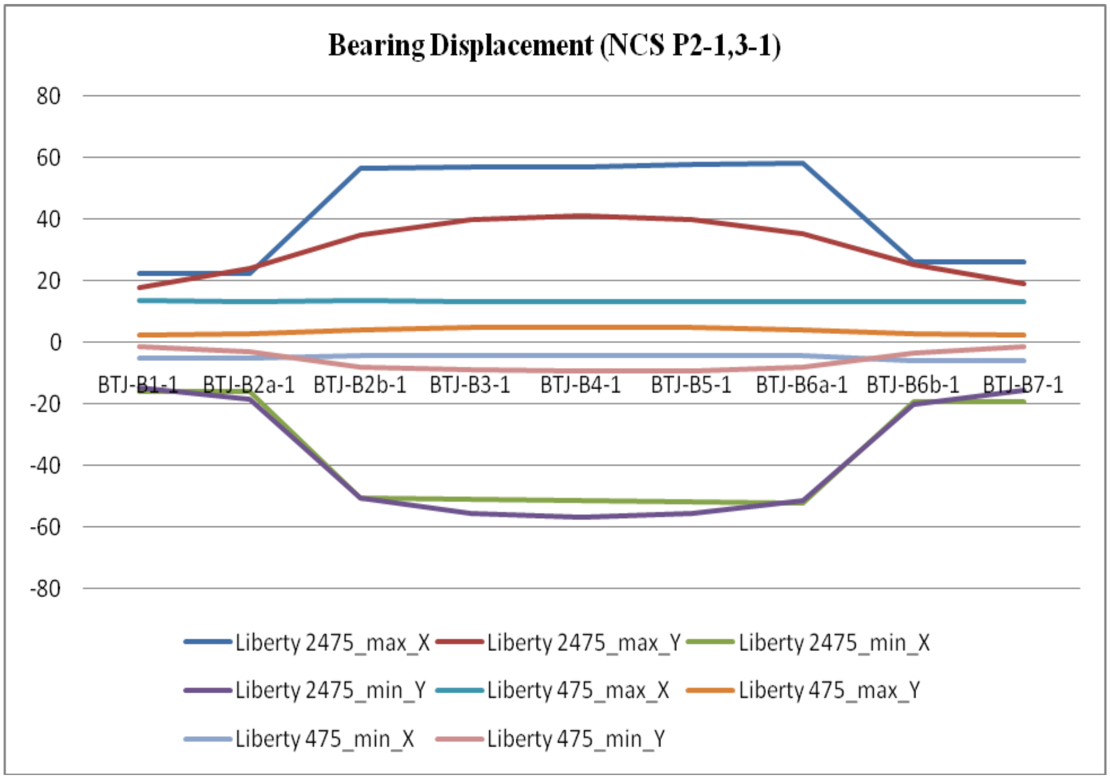

Bearing Displacement (NCS P1-1,1-2)
15
10
5
0
-5
-10
-15
-20
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Lowndes 2475_max_X
Lowndes 2475_max_Y
Lowndes 2475_min_X
Lowndes 2475_min_Y
Lowndes 475_max_X
Lowndes 475_max_Y
Lowndes 475_min_X
Lowndes 475_min_Y

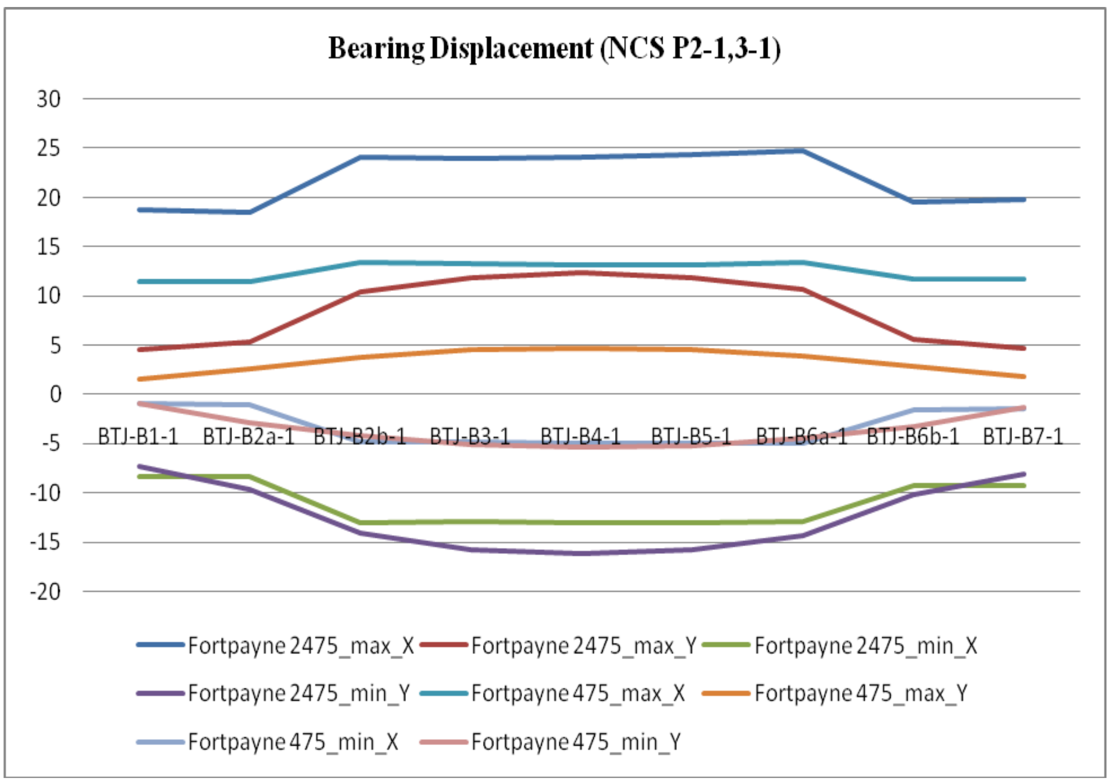


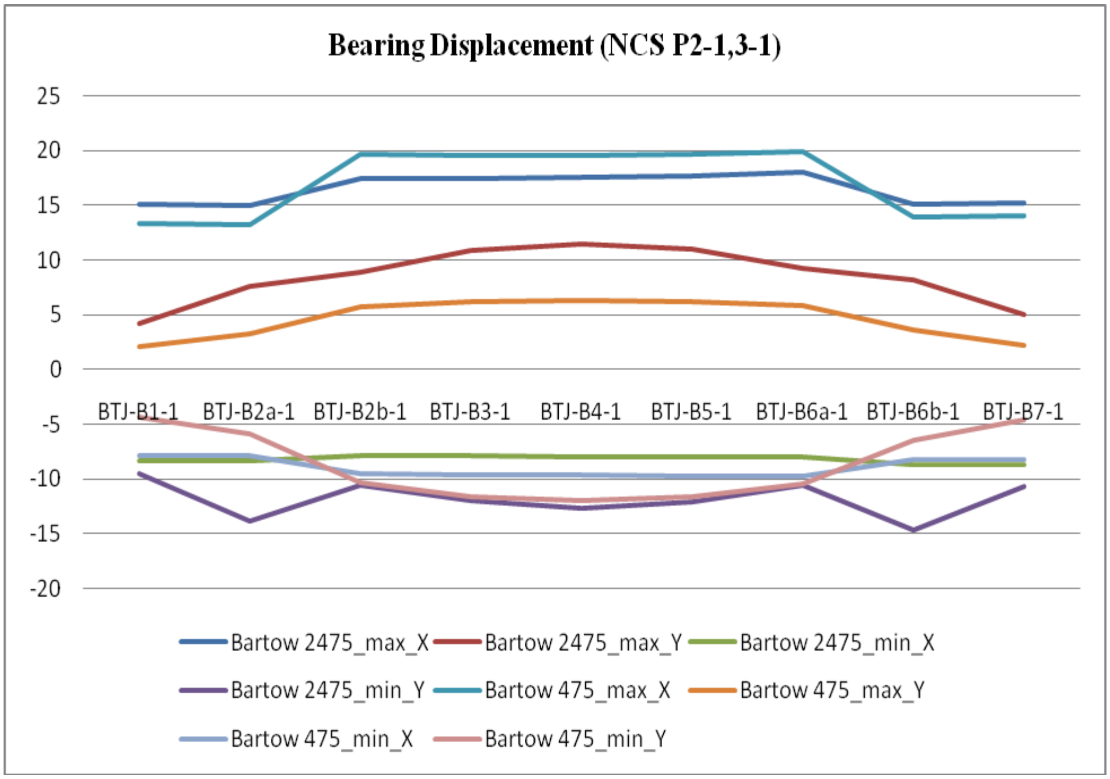
Bearing Displacement (NCS P2-1,3-1)
150
100
50
0
-50
-100
-150
-200
-250
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Northridge_Max_X
Northridge_max_Y
Northridge_min_X
Northridge_min_Y
ElCentro_max_X
ElCentro_max_Y
ElCentro_min_X
ElCentro_min_Y

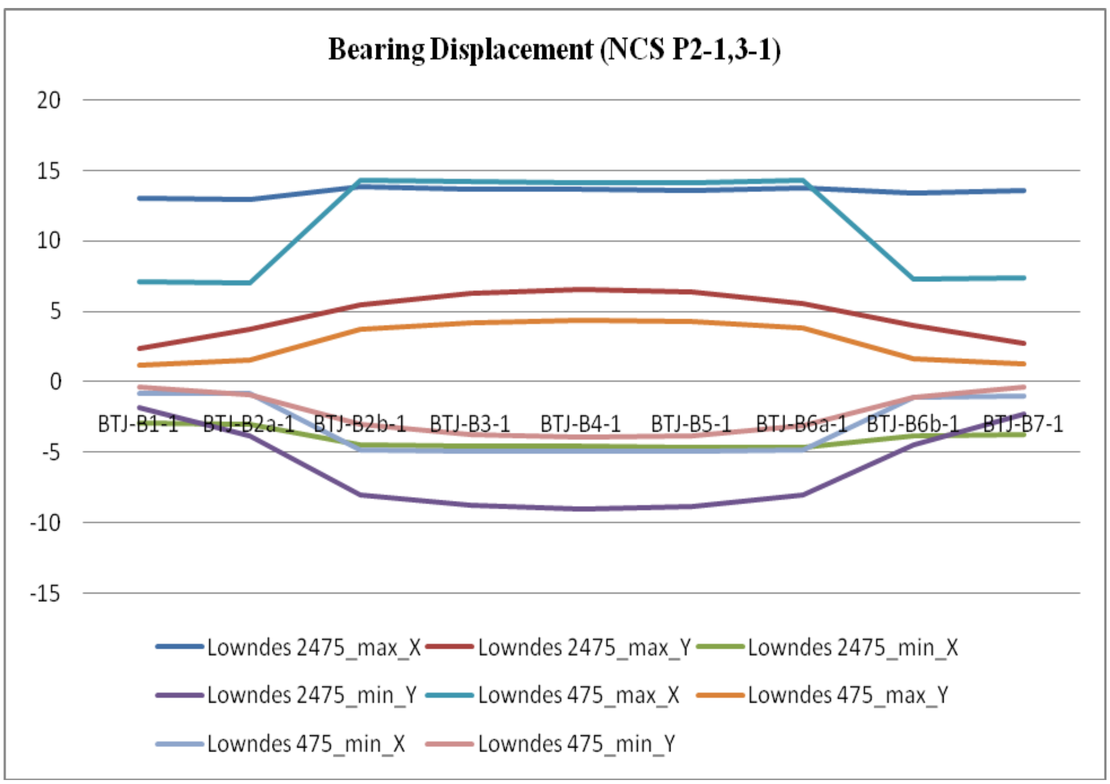


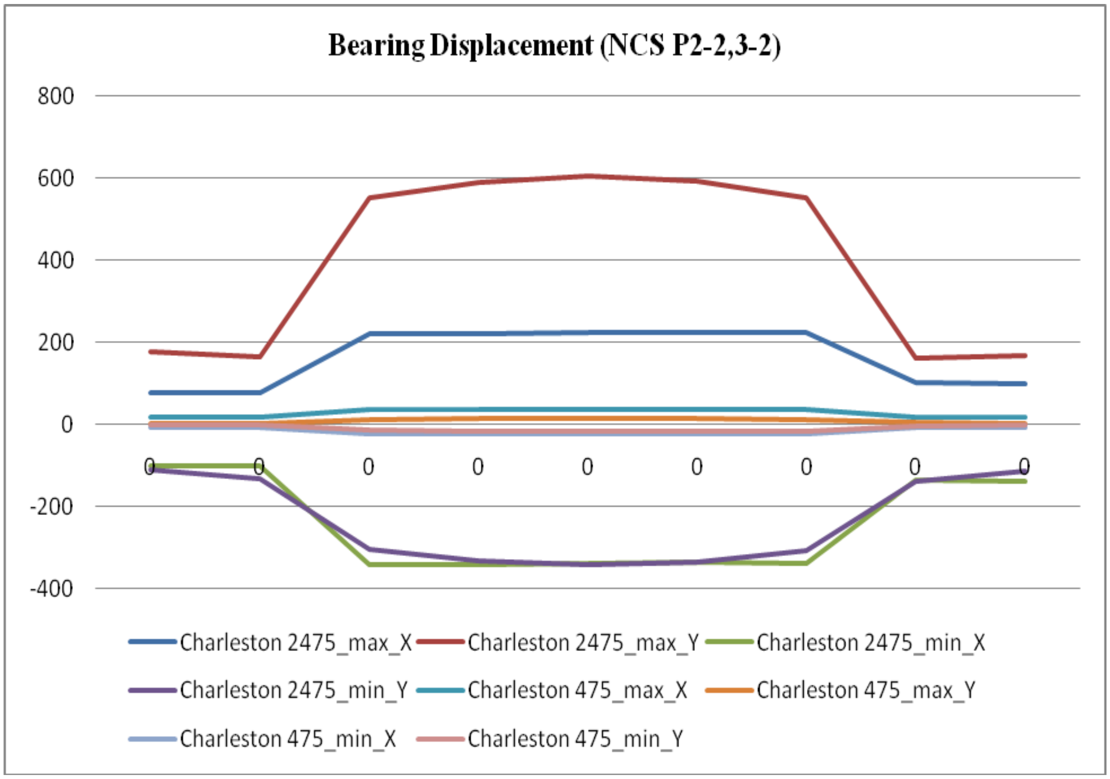
Bearing Displacement (NCS P2-1,3-1)
300
200
100
0
-100
-200
-300
-400
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Charleston 2475_max_X
Charleston 2475_max_Y
Charleston 2475_min_X
Charleston 2475_min_Y
Charleston 475_max_X
Charleston 475_max_Y
Charleston 475_min_X
Charleston 475_min_Y

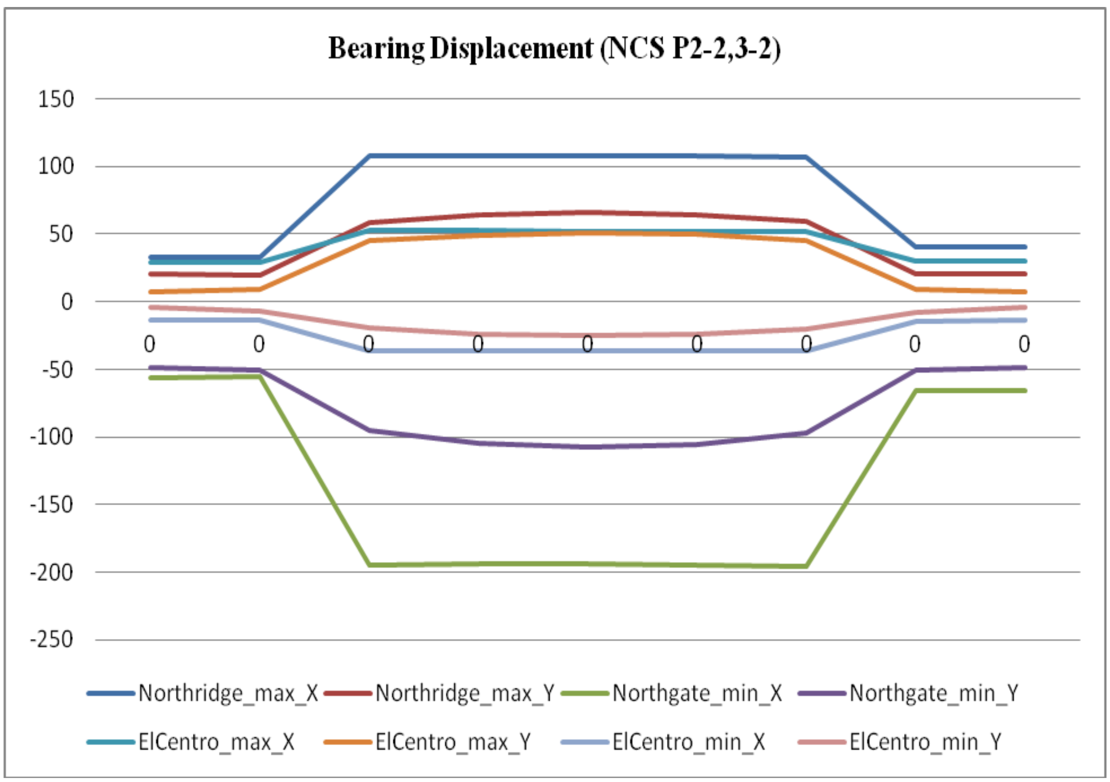

Bearing Displacement (NCS P2-1,3-1)
80
60
40
20
0
-20
-40
-60
-80
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Liberty 2475_max_X
Liberty 2475_max_Y
Liberty 2475_min_X
Liberty 2475_min_Y
Liberty 475_max_X
Liberty 475_max_Y
Liberty 475_min_X
Liberty 475_min_Y

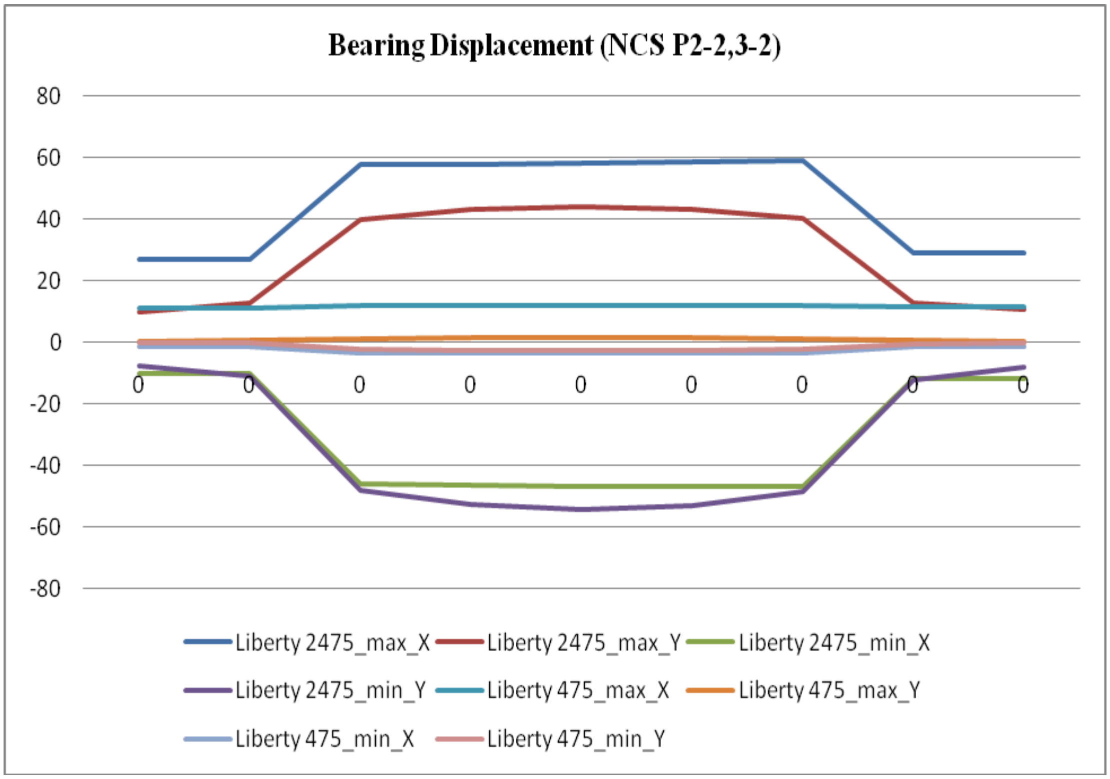

Bearing Displacement (NCS P2-1,3-1)
30
25
20
15
10
5
0
-5
-10
-15
-20
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Fortpayne 2475_max_X
Fortpayne 2475_max_Y
Fortpayne 2475_min_X
Fortpayne 2475_min_Y
Fortpayne 475_max_X
Fortpayne 475_max_Y
Fortpayne 475_min_X
Fortpayne 475_min_Y

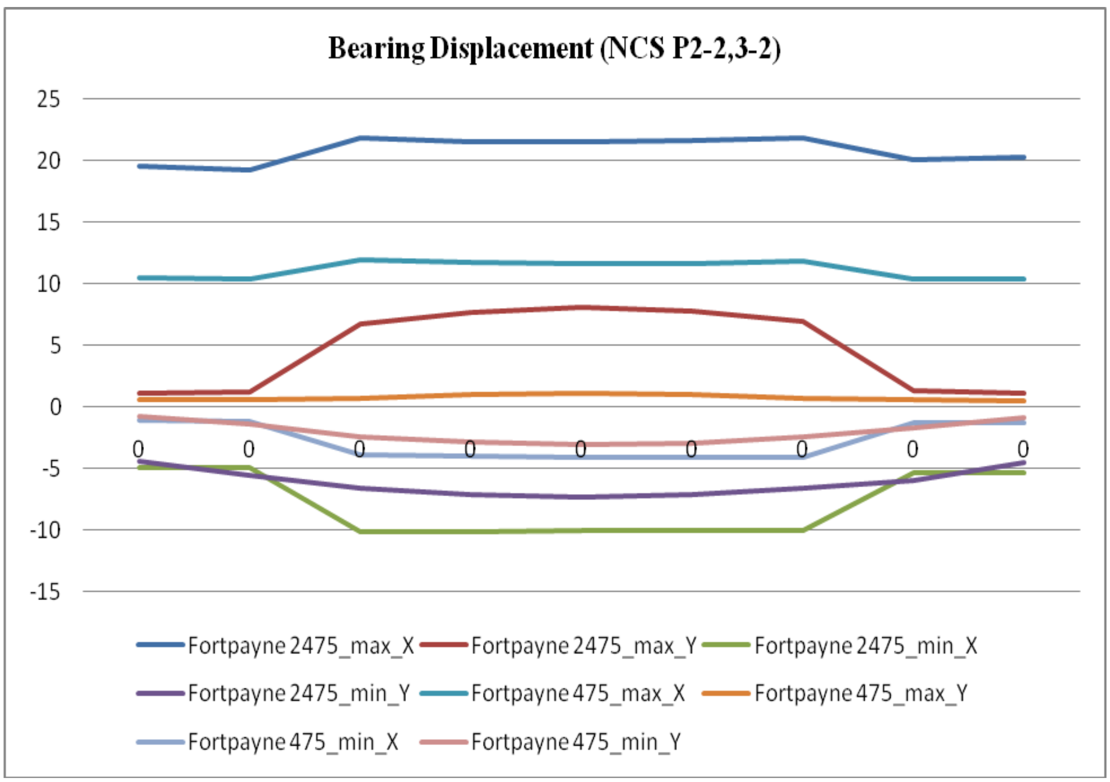

Bearing Displacement (NCS P2-1,3-1)
25
20
15
10
5
0
-5
-10
-15
-20
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Bartow 2475_max_X
Bartow 2475_max_Y
Bartow 2475_min_X
Bartow 2475_min_Y
Bartow 475_max_X
Bartow 475_max_Y
Bartow 475_min_X
Bartow 475_min_Y

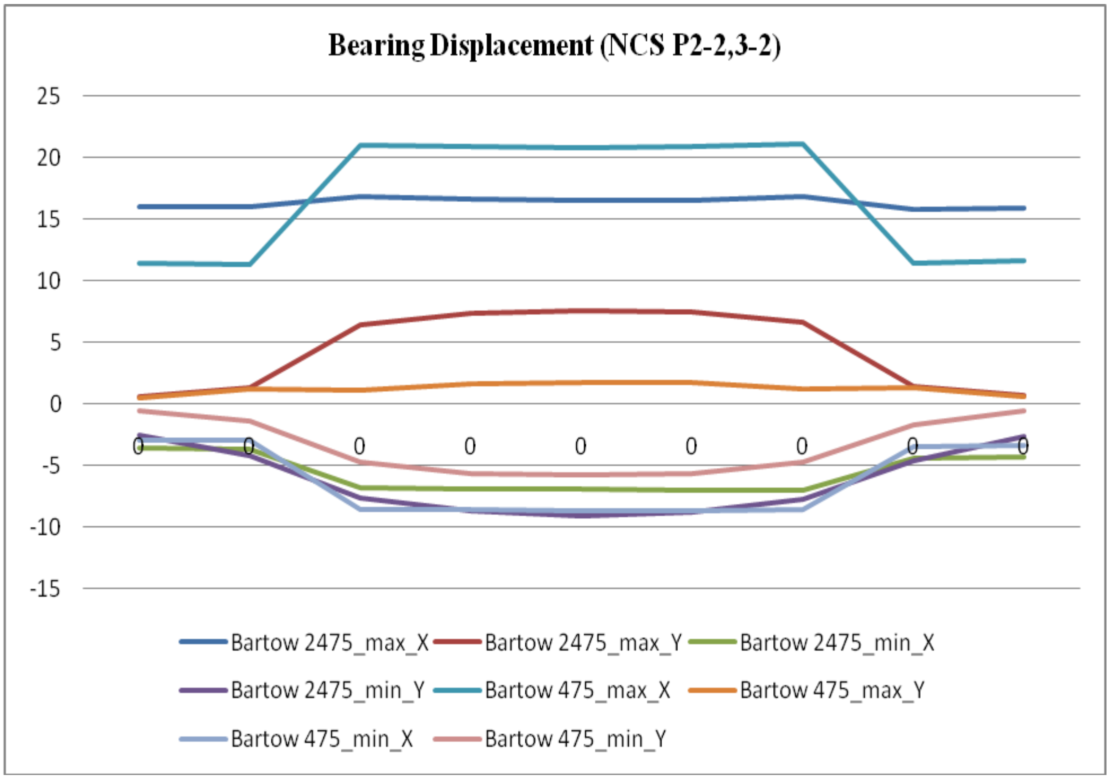

Bearing Displacement (NCS P2-1,3-1)
20
15
10
5
0
-5
-10
-15
BTJ-B1-1
BTJ-B2a-1
BTJ-B2b-1
BTJ-B3-1
BTJ-B4-1
BTJ-B5-1
BTJ-B6a-1
BTJ-B6b-1
BTJ-B7-1
Lowndes 2475_max_X
Lowndes 2475_max_Y
Lowndes 2475_min_X
Lowndes 2475_min_Y
Lowndes 475_max_X
Lowndes 475_max_Y
Lowndes 475_min_X
Lowndes 475_min_Y

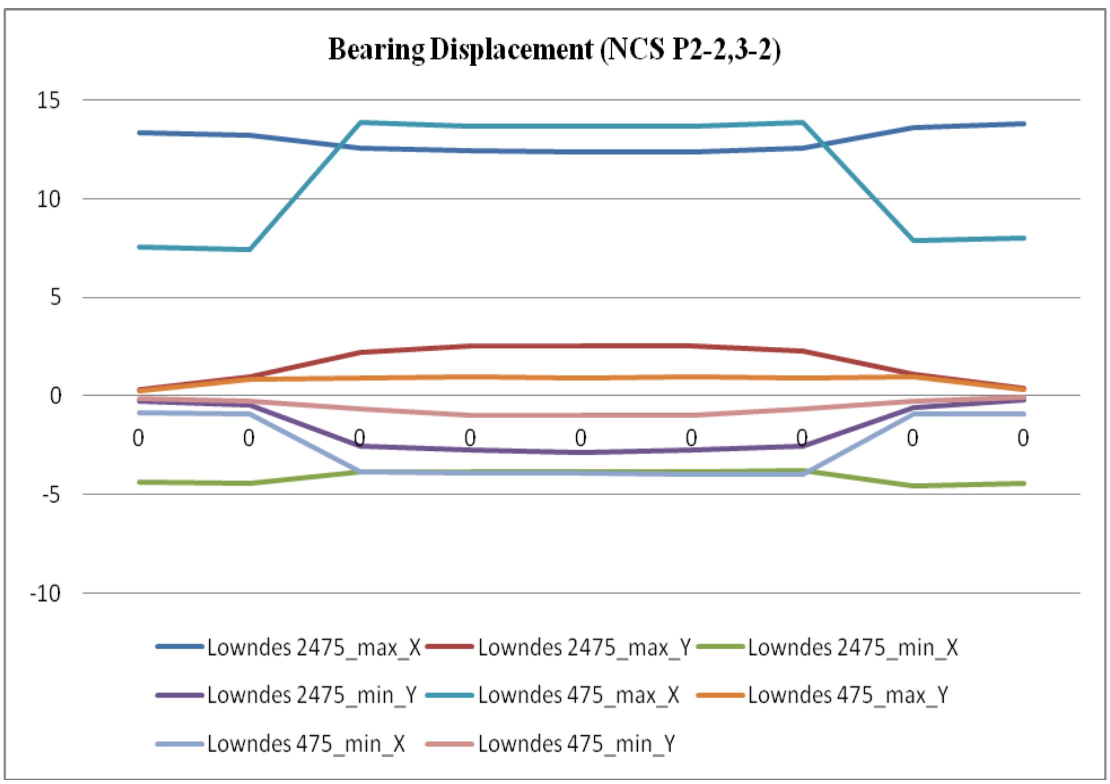

Bearing Displacement (NCS P2-2,3-2)
800
600
400
200
0
-200
-400
0 0 0 0 0 0 0 0 0
Charleston 2475_max_X
Charleston 2475_max_Y
Charleston 2475_min_X
Charleston 2475_min_Y
Charleston 475_max_X
Charleston 475_max_Y
Charleston 475_min_X
Charleston 475_min_Y

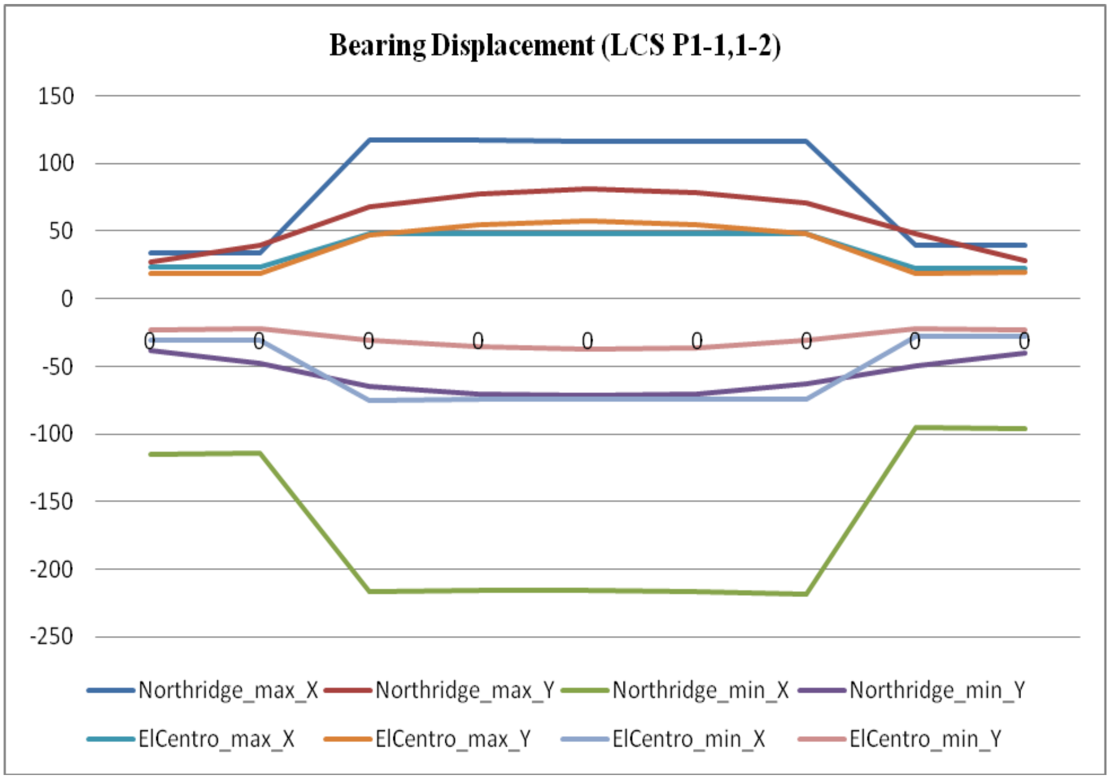

Bearing Displacement (NCS P2-2,3-2)
150
100
50
0
-50
-100
-150
-200
-250
0 0 0 0 0 0 0 0 0
Northridge_max_X
Northridge_max_Y
Northgate_min_X
Northgate_min_Y
ElCentro_max_X
ElCentro_max_Y
ElCentro_min_X
ElCentro_min_Y

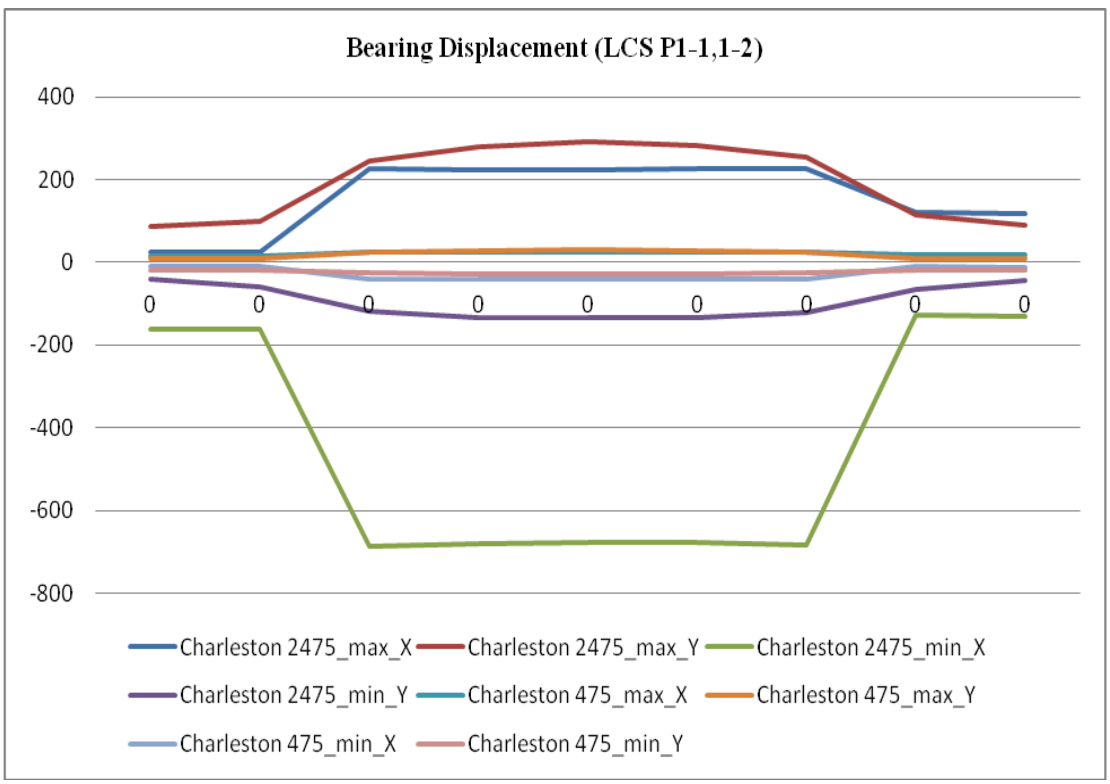

Bearing Displacement (NCS P2-2,3-2)
80
60
40
20
0
-20
-40
-60
-80
0 0 0 0 0 0 0 0 0
Liberty 2475_max_X
Liberty 2475_max_Y
Liberty 2475_min_X
Liberty 2475_min_Y
Liberty 475_max_X
Liberty 475_max_Y
Liberty 475_min_X
Liberty 475_min_Y

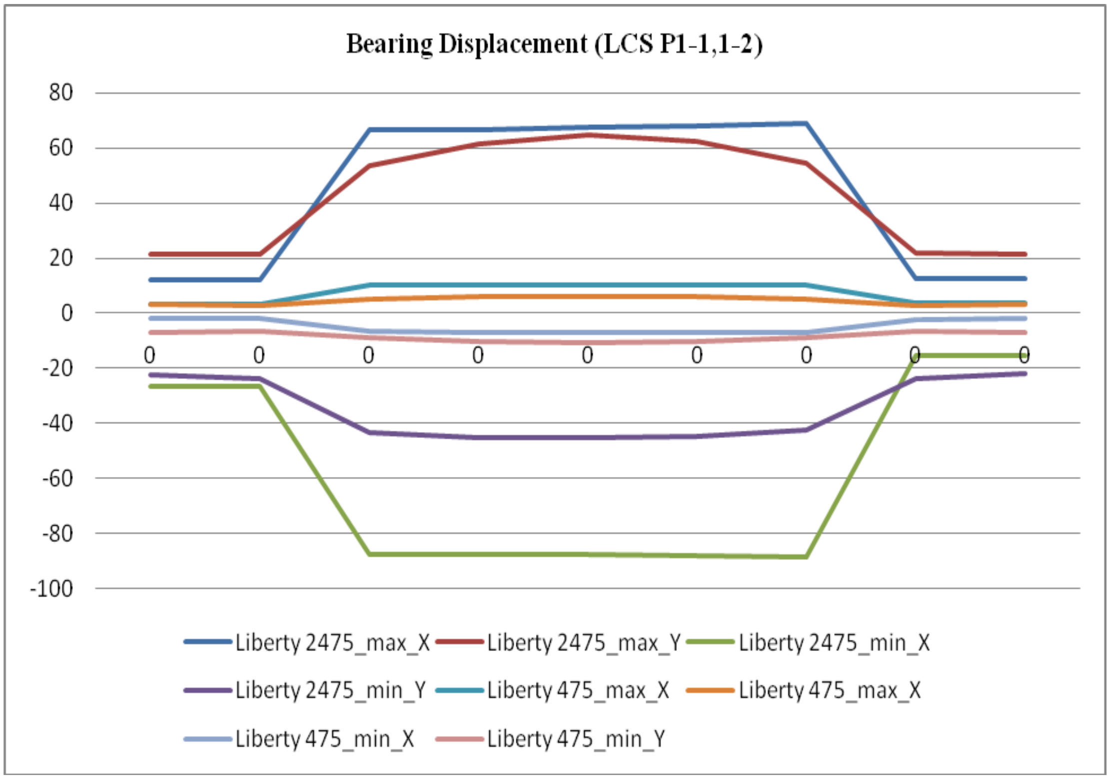

Bearing Displacement (NCS P2-2,3-2)
25
20
15
10
5
0
-5
-10
-15
0 0 0 0 0 0 0 0 0
Fortpayne 2475_max_X
Fortpayne 2475_max_Y
Fortpayne 2475_min_X
Fortpayne 2475_min_Y
Fortpayne 475_max_X
Fortpayne 475_max_Y
Fortpayne 475_min_X
Fortpayne 475_min_Y

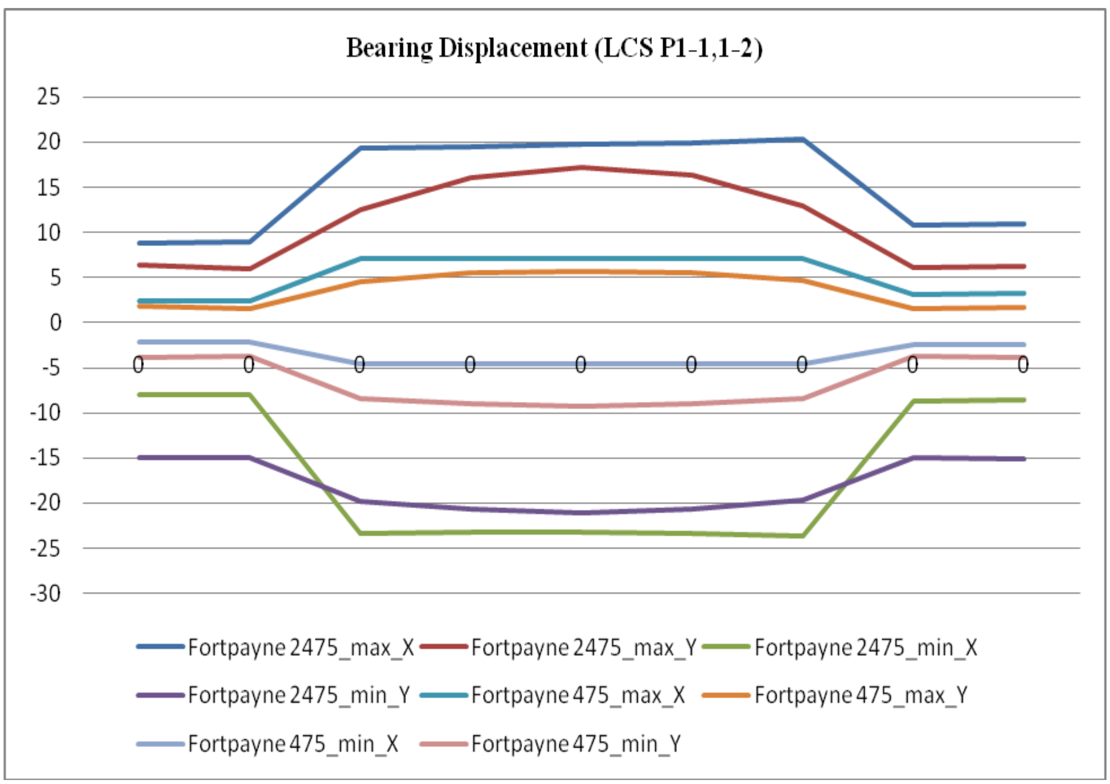

Bearing Displacement (NCS P2-2,3-2)
25
20
15
10
5
0
-5
-10
-15
0 0 0 0 0 0 0 0 0
Bartow 2475_max_X
Bartow 2475_max_Y
Bartow 2475_min_X
Bartow 2475_min_Y
Bartow 475_max_X
Bartow 475_max_Y
Bartow 475_min_X
Bartow 475_min_Y

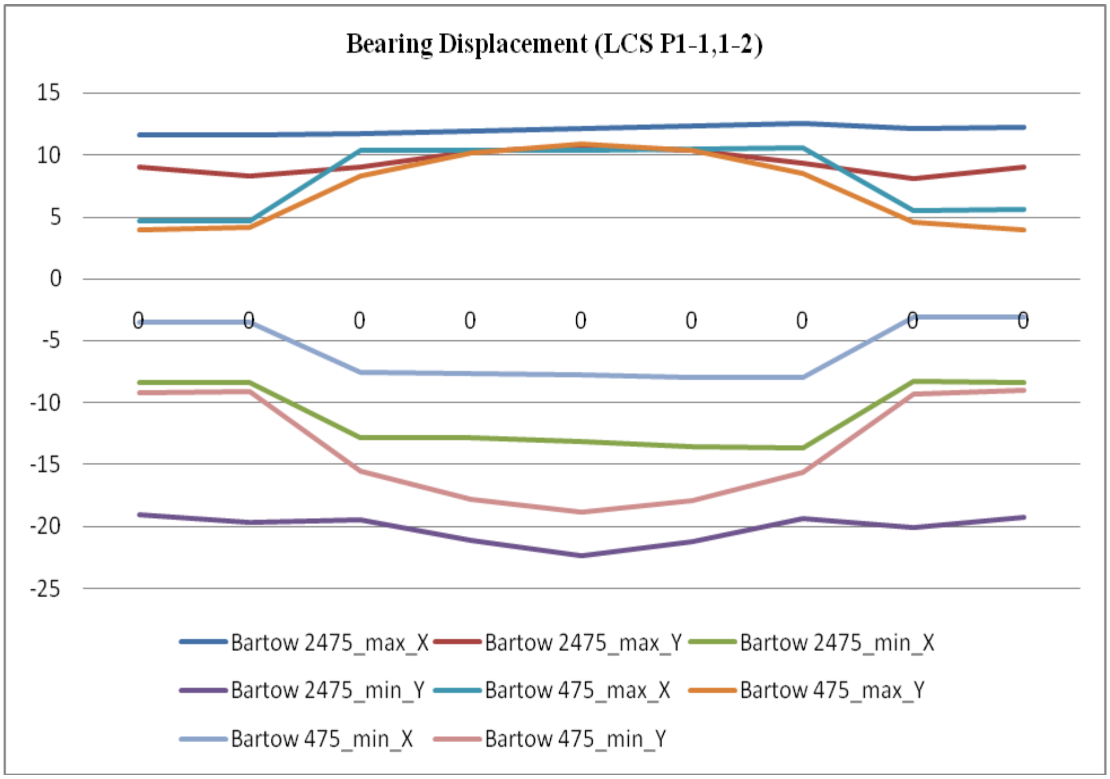

Bearing Displacement (NCS P2-2,3-2)
15
10
5
0
-5
-10
0 0 0 0 0 0 0 0 0
Lowndes 2475_max_X
Lowndes 2475_max_Y
Lowndes 2475_min_X
Lowndes 2475_min_Y
Lowndes 475_max_X
Lowndes 475_max_Y
Lowndes 475_min_X
Lowndes 475_min_Y

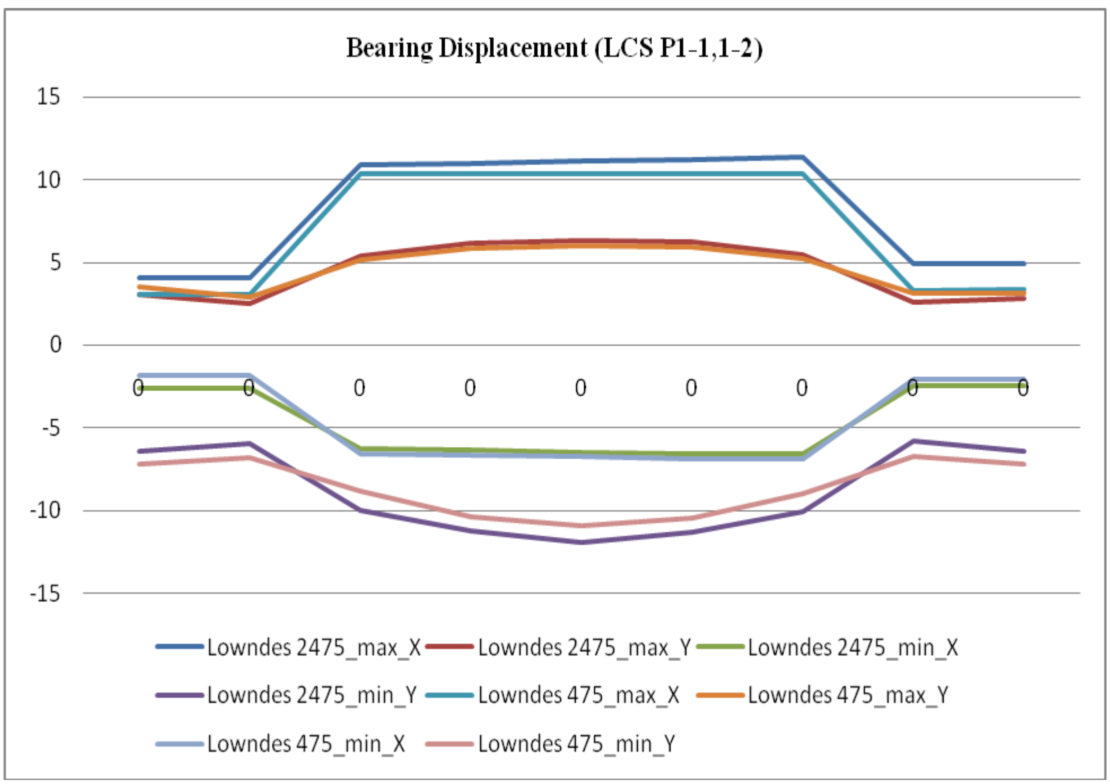

Bearing Displacement (LCS P1-1,1-2)
150
100
50
0
-50
-100
-150
-200
-250
0
0
0
0
0
0
0
0
0
Northridge_max_X
Northridge_max_Y
Northridge_min_X
Northridge_min_Y
ElCentro_max_X
ElCentro_max_Y
ElCentro_min_X
ElCentro_min_Y

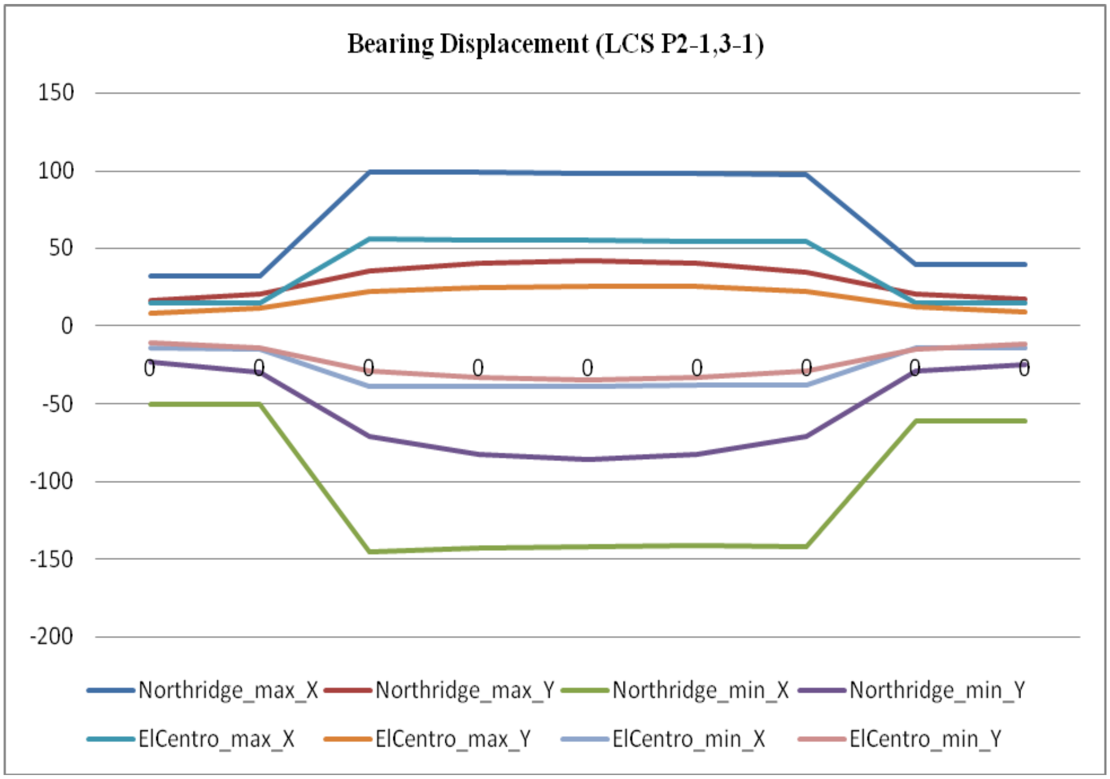

Bearing Displacement (LCS P1-1,1-2)
400
200
0
-200
-400
-600
-800
0
0
0
0
0
0
0
0
0
Charleston 2475_max_X
Charleston 2475_max_Y
Charleston 2475_min_X
Charleston 2475_min_Y
Charleston 475_max_X
Charleston 475_max_Y
Charleston 475_min_X
Charleston 475_min_Y


Bearing Displacement (LCS P1-1,1-2)
80
60
40
20
0
-20
-40
-60
-80
-100
0
Liberty 2475_max_X
Liberty 2475_max_Y
Liberty 2475_min_X
Liberty 2475_min_Y
Liberty 475_max_X
Liberty 475_max_X
Liberty 475_min_X
Liberty 475_min_Y

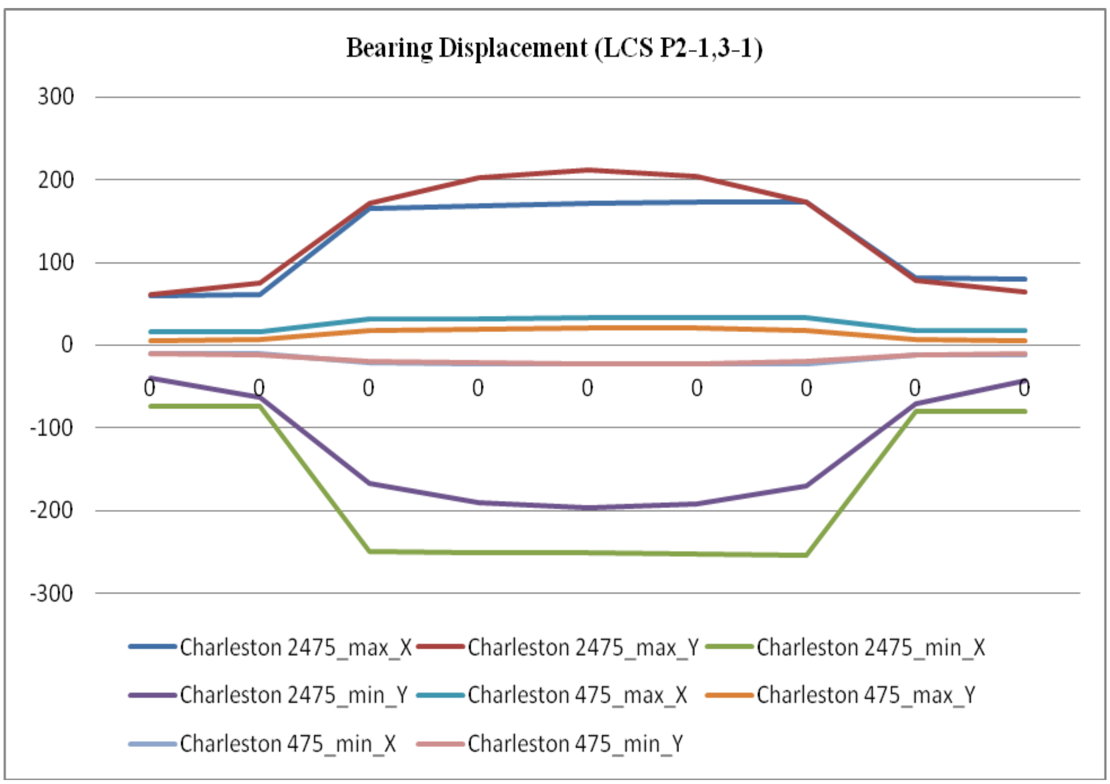

Bearing Displacement (LCS P1-1,1-2)
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
0
Fortpayne 2475_max_X
Fortpayne 2475_max_Y
Fortpayne 2475_min_X
Fortpayne 2475_min_Y
Fortpayne 475_max_X
Fortpayne 475_max_Y
Fortpayne 475_min_X
Fortpayne 475_min_Y


Bearing Displacement (LCS P1-1,1-2)
15
10
5
0
-5
-10
-15
-20
-25
0 0 0 0 0 0 0 0 0
Bartow 2475_max_X
Bartow 2475_max_Y
Bartow 2475_min_X
Bartow 2475_min_Y
Bartow 475_max_X
Bartow 475_max_Y
Bartow 475_min_X
Bartow 475_min_Y

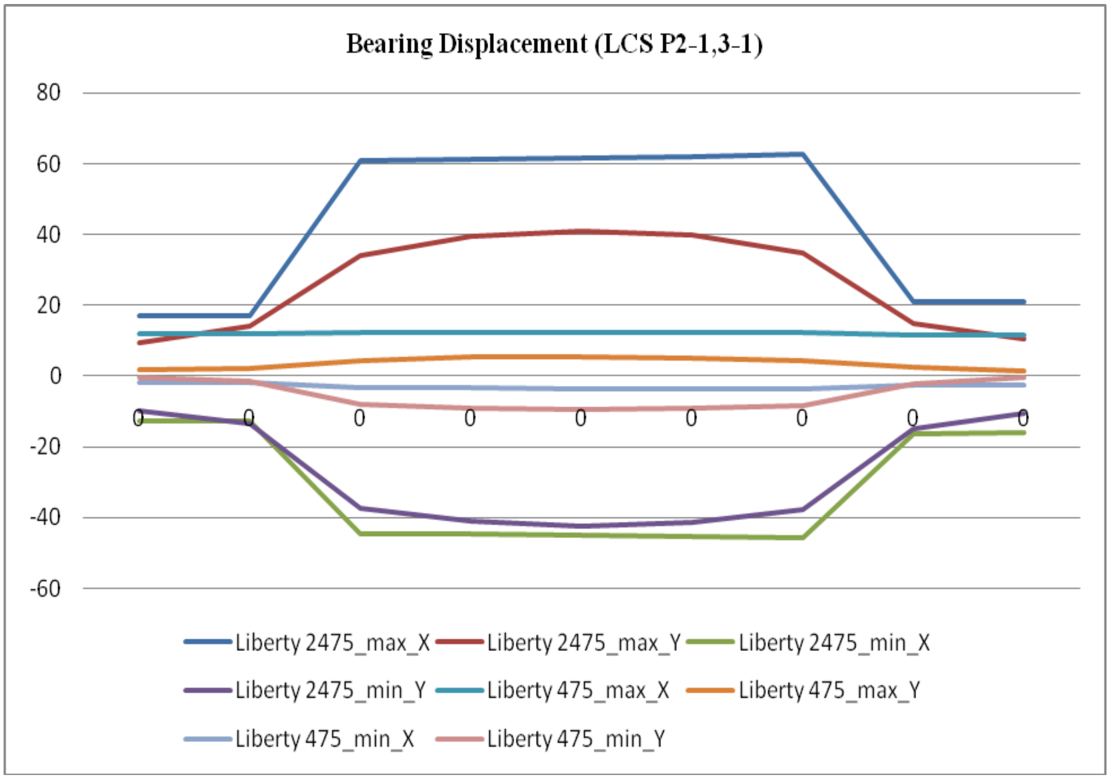

Bearing Displacement (LCS P1-1,1-2)
15
10
5
0
-5
-10
-15
0 0 0 0 0 0 0 0 0
Lowndes 2475_max_X
Lowndes 2475_max_Y
Lowndes 2475_min_X
Lowndes 2475_min_Y
Lowndes 475_max_X
Lowndes 475_max_Y
Lowndes 475_min_X
Lowndes 475_min_Y

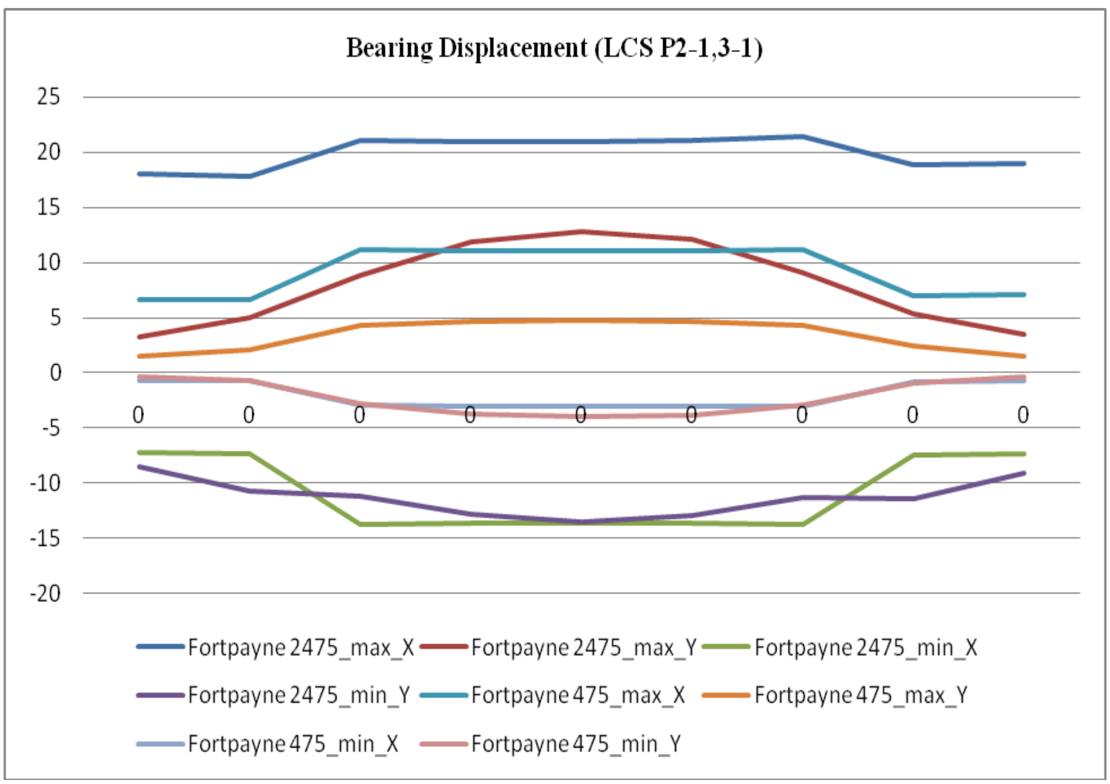


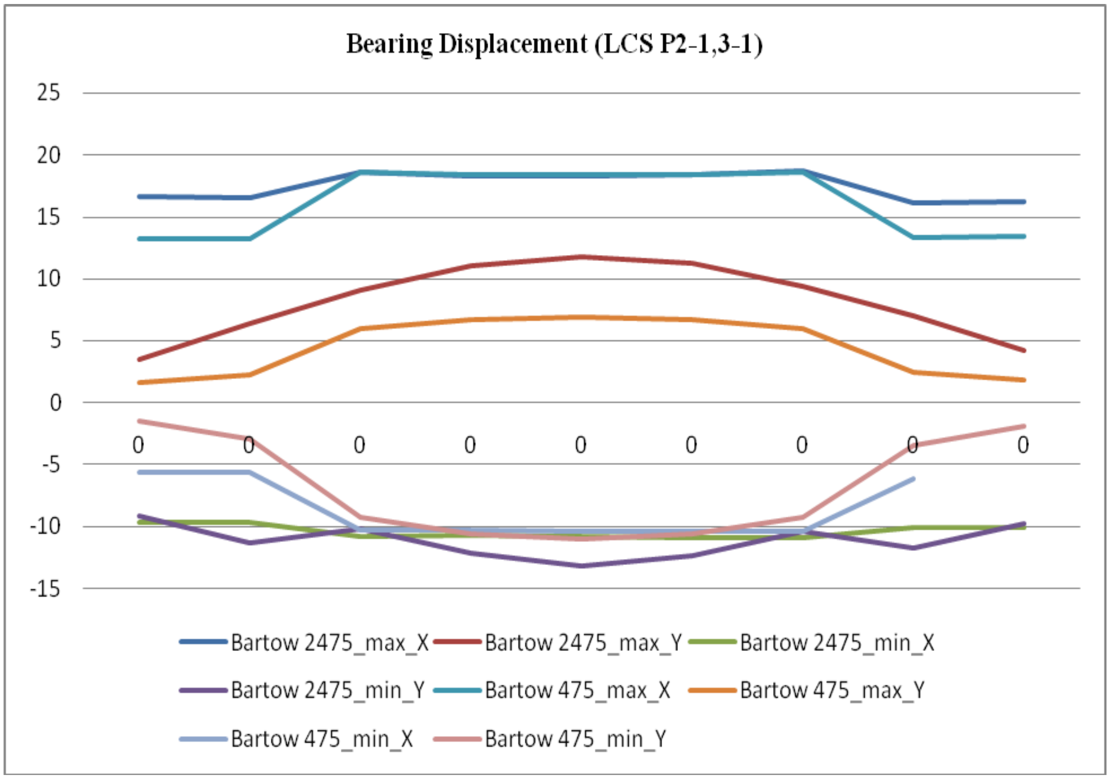
Bearing Displacement (LCS P2-1,3-1)
150
100
50
0
-50
-100
-150
-200
0
Northridge_max_X
Northridge_max_Y
Northridge_min_X
Northridge_min_Y
ElCentro_max_X
ElCentro_max_Y
ElCentro_min_X
ElCentro_min_Y



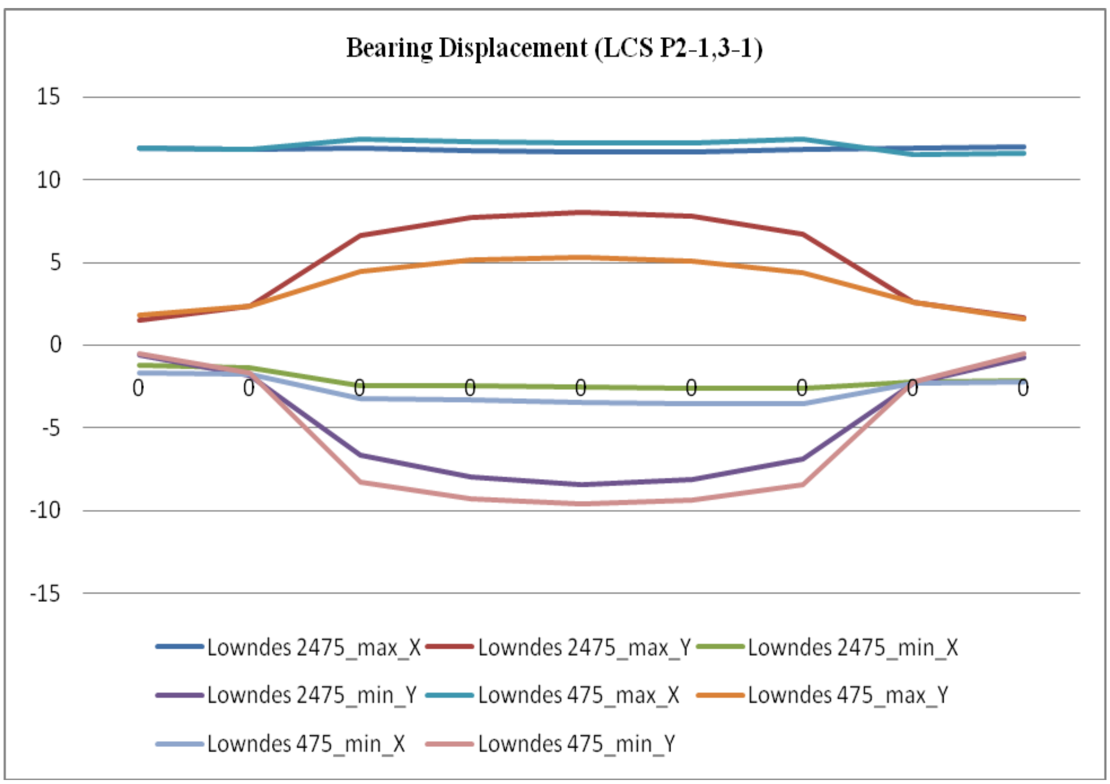
Bearing Displacement (LCS P2-1,3-1)
300
200
100
0
-100
-200
-300
0
Charleston 2475_max_X
Charleston 2475_max_Y
Charleston 2475_min_X
Charleston 2475_min_Y
Charleston 475_max_X
Charleston 475_max_Y
Charleston 475_min_X
Charleston 475_min_Y


Bearing Displacement (LCS P2-1,3-1)
80
60
40
20
0
-20
-40
-60
0 0 0 0 0 0 0 0 0
Liberty 2475_max_X
Liberty 2475_max_Y
Liberty 2475_min_X
Liberty 2475_min_Y
Liberty 475_max_X
Liberty 475_max_Y
Liberty 475_min_X
Liberty 475_min_Y

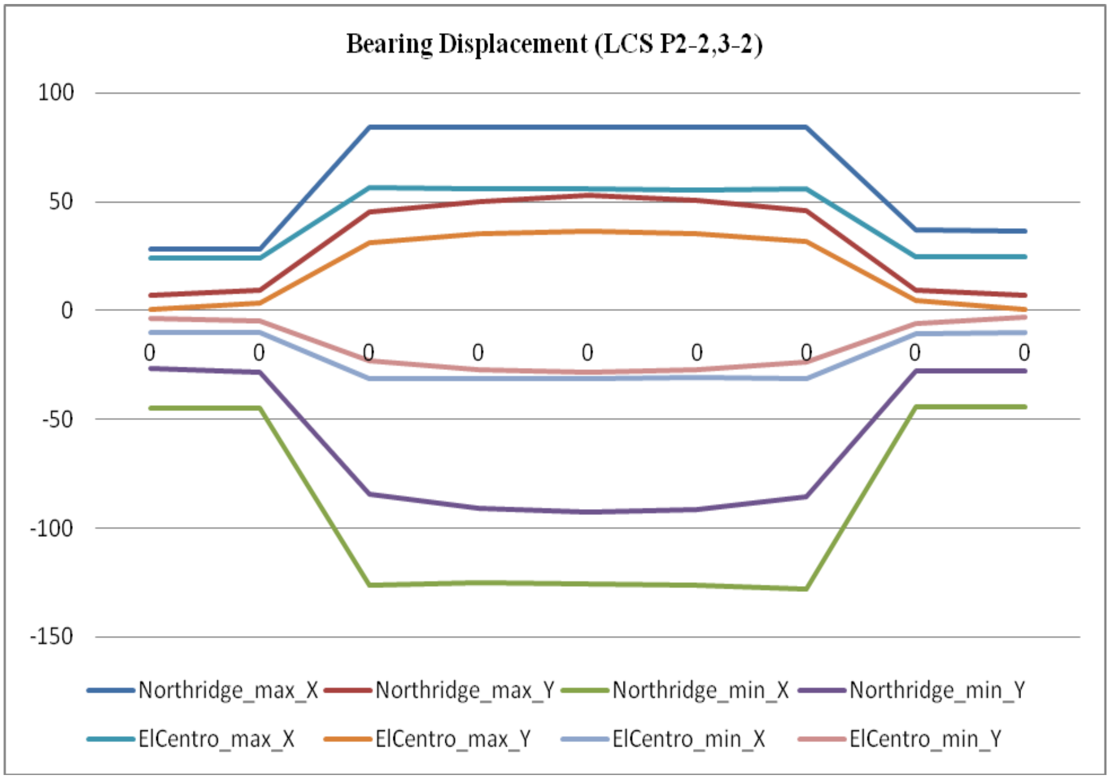

Bearing Displacement (LCS P2-1,3-1)
25
20
15
10
5
0
-5
-10
-15
-20
0 0 0 0 0 0 0 0 0
Fortpayne 2475_max_X
Fortpayne 2475_max_Y
Fortpayne 2475_min_X
Fortpayne 2475_min_Y
Fortpayne 475_max_X
Fortpayne 475_max_Y
Fortpayne 475_min_X
Fortpayne 475_min_Y

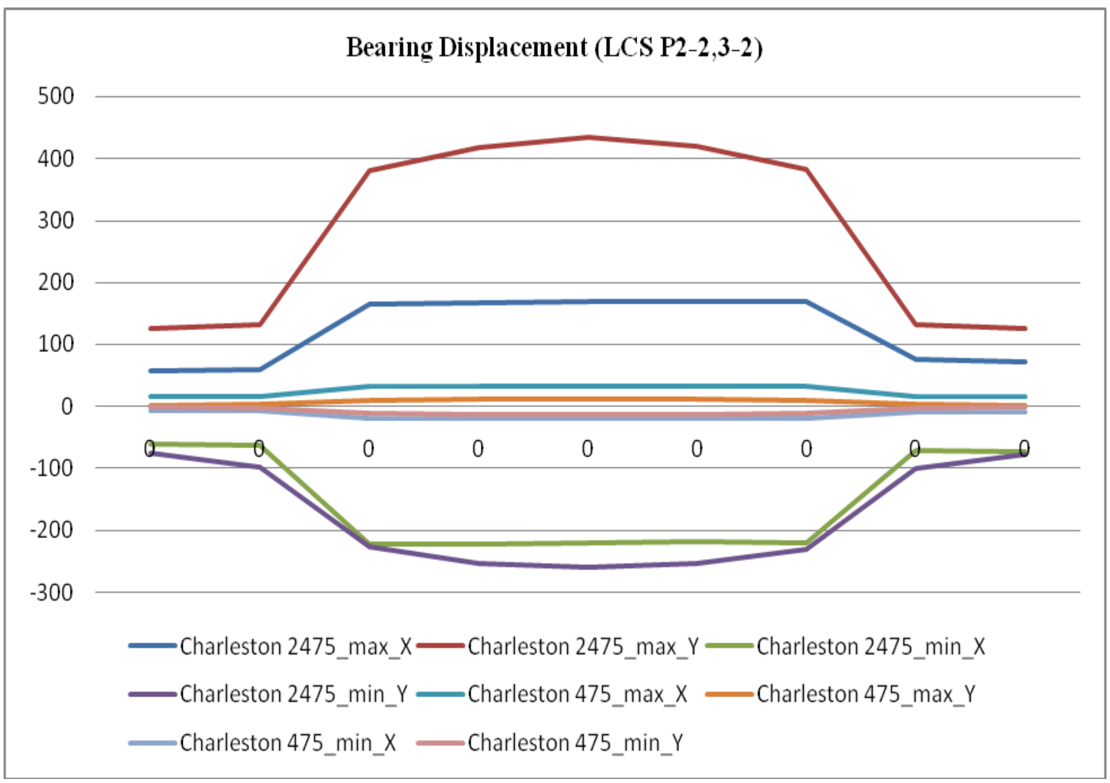


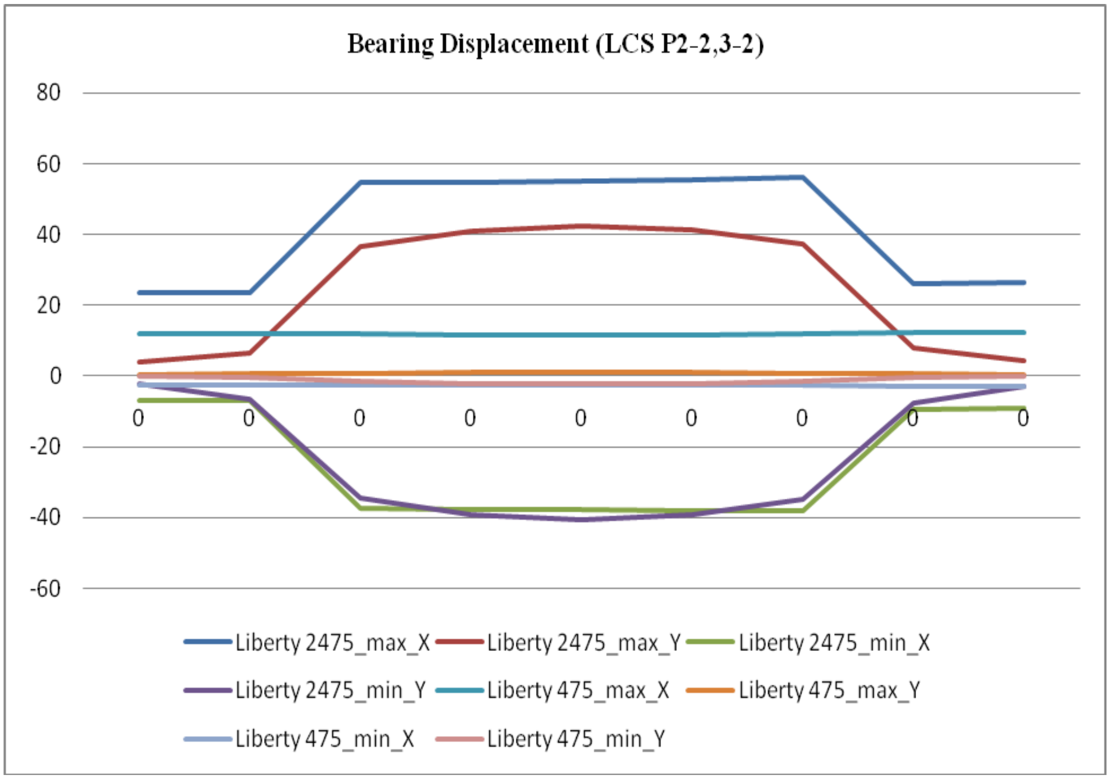
Bearing Displacement (LCS P2-1,3-1)
25
20
15
10
5
0
-5
-10
-15
0 0 0 0 0 0 0 0 0
Bartow 2475_max_X
Bartow 2475_max_Y
Bartow 2475_min_X
Bartow 2475_min_Y
Bartow 475_max_X
Bartow 475_max_Y
Bartow 475_min_X
Bartow 475_min_Y

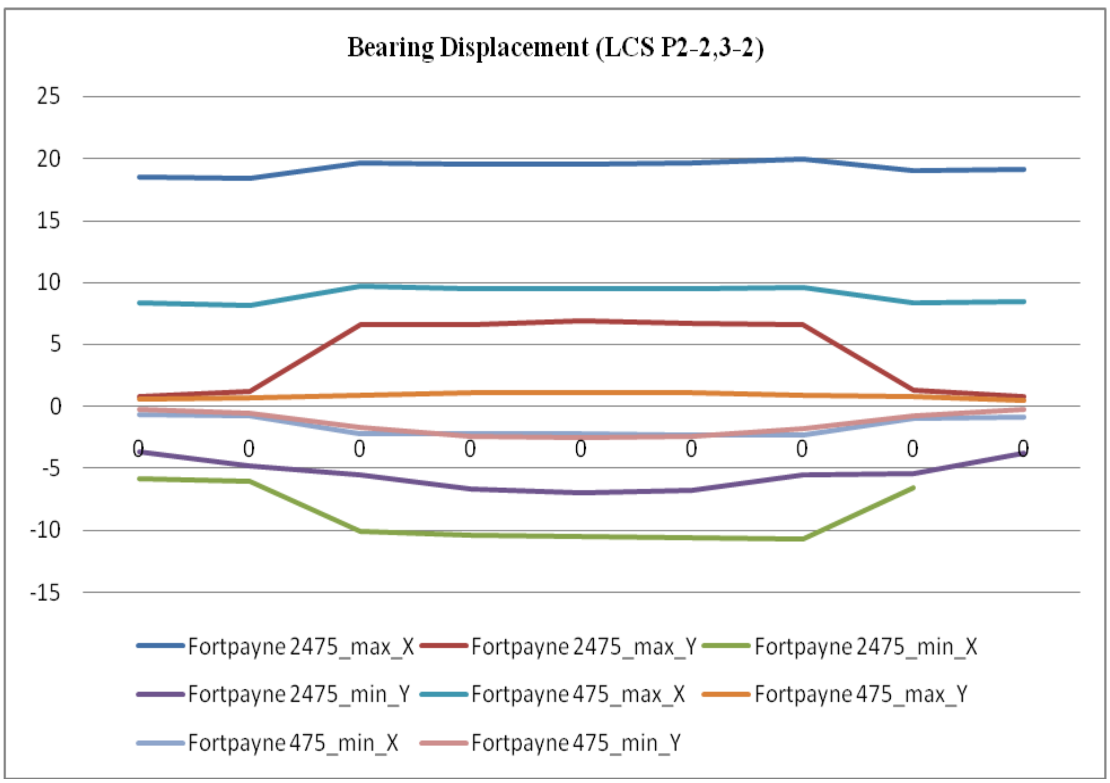


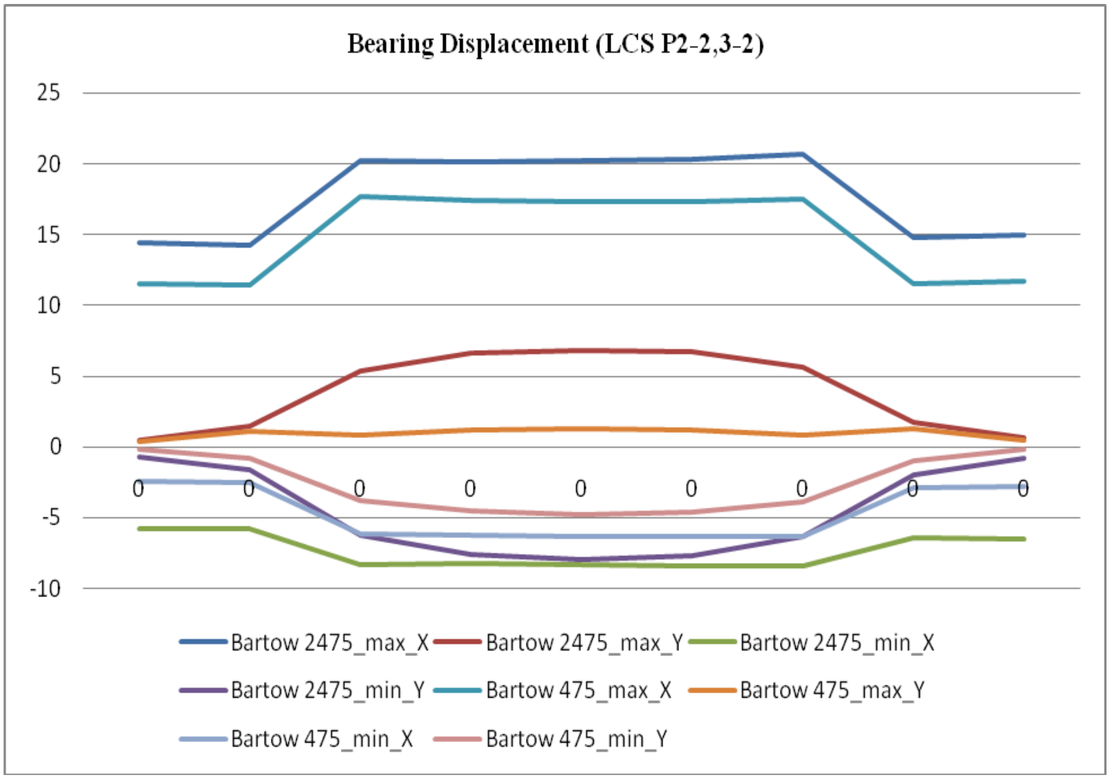
Bearing Displacement (LCS P2-1,3-1)
15
10
5
0
-5
-10
-15
0 0 0 0 0 0 0 0 0
Lowndes 2475_max_X
Lowndes 2475_max_Y
Lowndes 2475_min_X
Lowndes 2475_min_Y
Lowndes 475_max_X
Lowndes 475_max_Y
Lowndes 475_min_X
Lowndes 475_min_Y

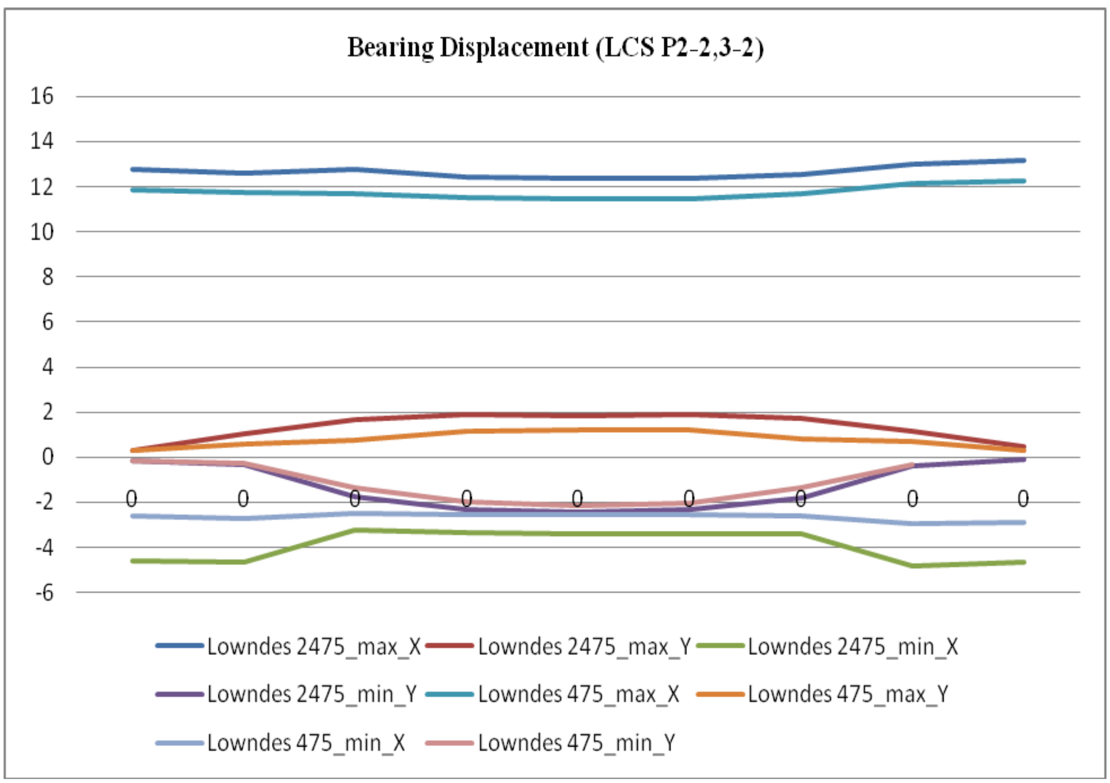

Bearing Displacement (LCS P2-2,3-2)
100
50
0
-50
-100
-150
0 0 0 0 0 0 0 0 0
Northridge_max_X
Northridge_max_Y
Northridge_min_X
Northridge_min_Y
ElCentro_max_X
ElCentro_max_Y
ElCentro_min_X
ElCentro_min_Y

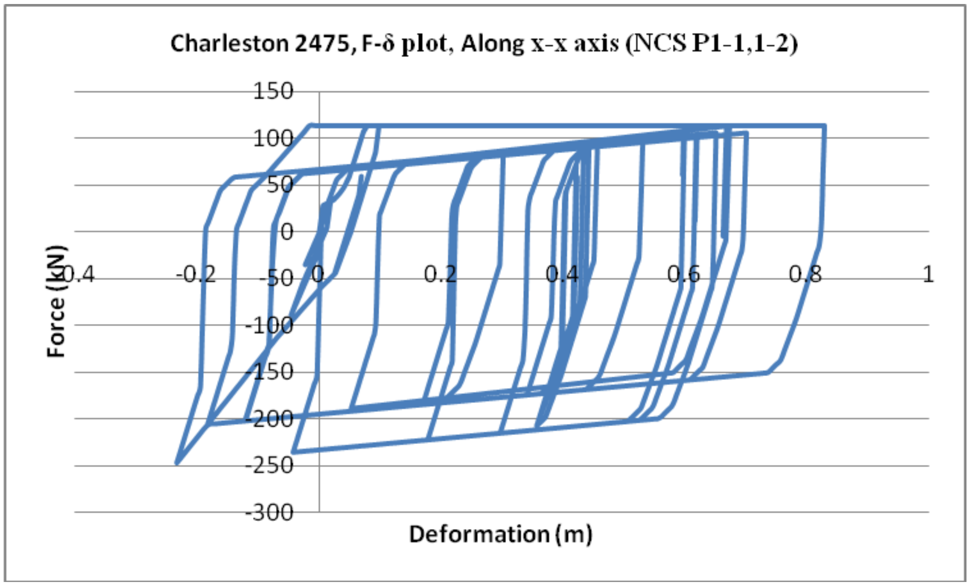

Bearing Displacement (LCS P2-2,3-2)
500
400
300
200
100
0
-100
-200
-300
0 0 0 0 0 0 0 0 0
Charleston 2475_max_X
Charleston 2475_max_Y
Charleston 2475_min_X
Charleston 2475_min_Y
Charleston 475_max_X
Charleston 475_max_Y
Charleston 475_min_X
Charleston 475_min_Y

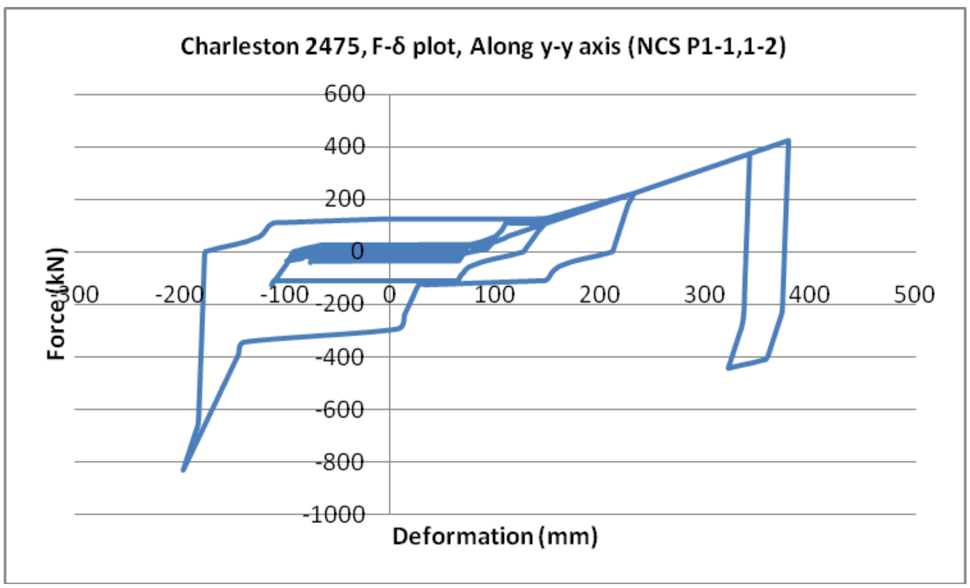

Bearing Displacement (LCS P2-2,3-2)
80
60
40
20
0
-20
-40
-60
0
0
0
0
0
0
0
0
0
Liberty 2475_max_X
Liberty 2475_max_Y
Liberty 2475_min_X
Liberty 2475_min_Y
Liberty 475_max_X
Liberty 475_max_Y
Liberty 475_min_X
Liberty 475_min_Y

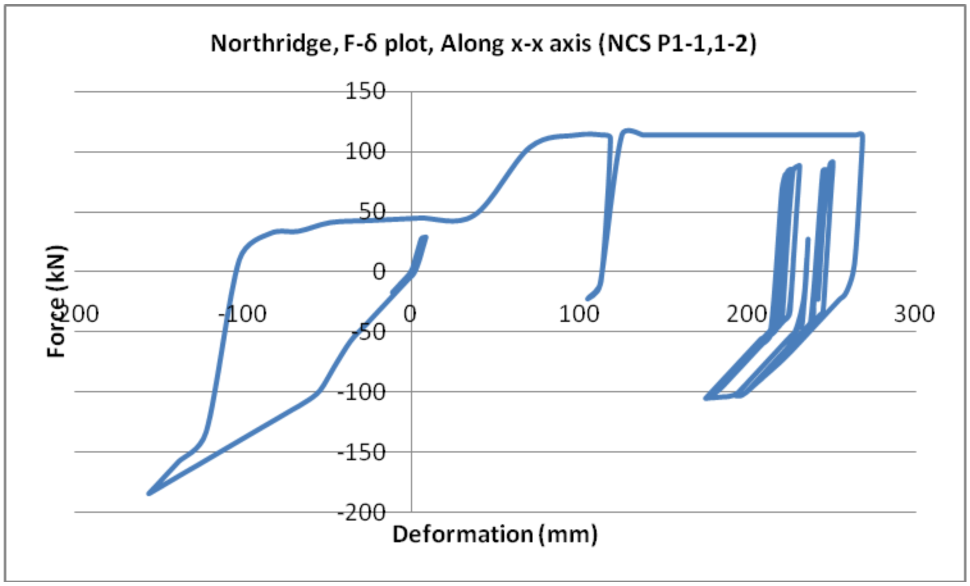

Bearing Displacement (LCS P2-2,3-2)
25
20
15
10
5
0
-5
-10
-15
0
0
0
0
0
0
0
0
0
Fortpayne 2475_max_X
Fortpayne 2475_max_Y
Fortpayne 2475_min_X
Fortpayne 2475_min_Y
Fortpayne 475_max_X
Fortpayne 475_max_Y
Fortpayne 475_min_X
Fortpayne 475_min_Y

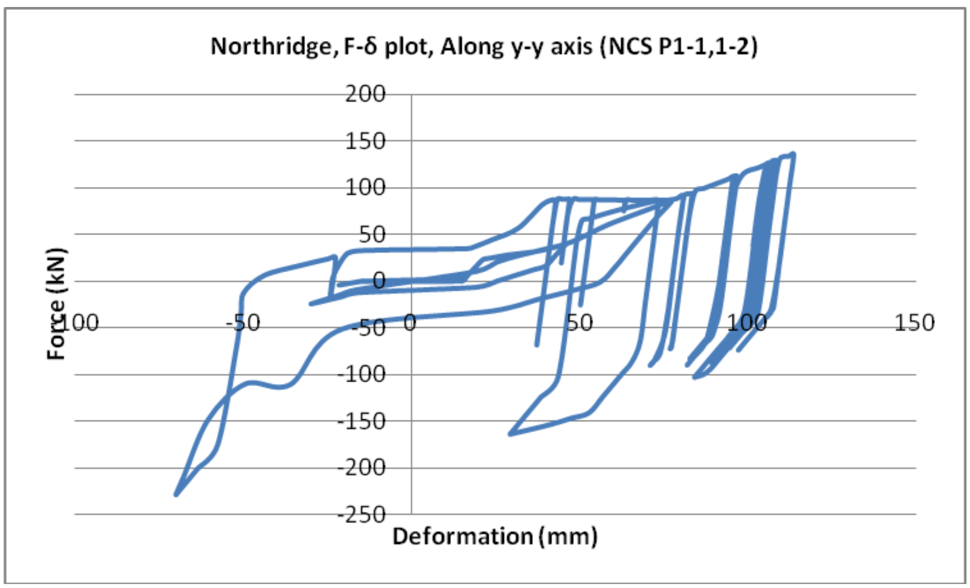

Bearing Displacement (LCS P2-2,3-2)
25
20
15
10
5
0
-5
-10
0
Bartow 2475_max_X
Bartow 2475_max_Y
Bartow 2475_min_X
Bartow 2475_min_Y
Bartow 475_max_X
Bartow 475_max_Y
Bartow 475_min_X
Bartow 475_min_Y

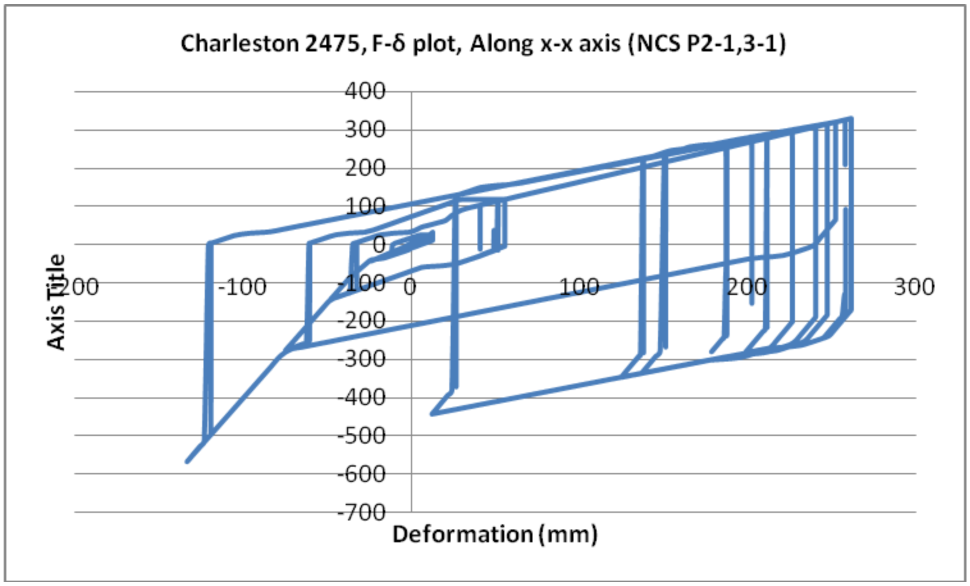

Bearing Displacement (LCS P2-2,3-2)
16
14
12
10
8
6
4
2
0
-2
-4
-6
0
Lowndes 2475_max_X
Lowndes 2475_max_Y
Lowndes 2475_min_X
Lowndes 2475_min_Y
Lowndes 475_max_X
Lowndes 475_max_Y
Lowndes 475_min_X
Lowndes 475_min_Y

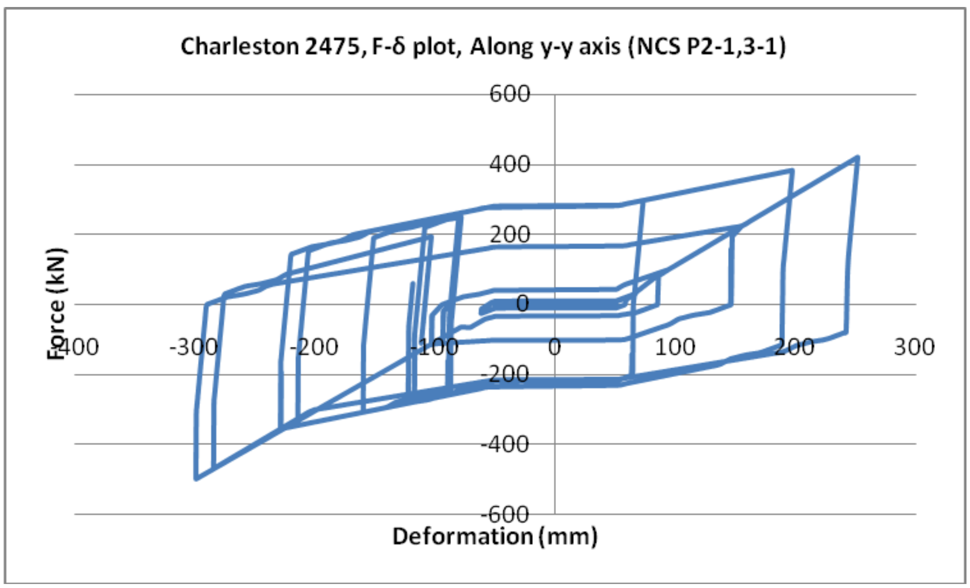

Charleston 2475, F-δ plot, Along x-x axis (NCS P1-1,1-2)
150
100
50
0
-50
-100
-150
-200
-250
-300
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Force (kN)
Deformation (m)

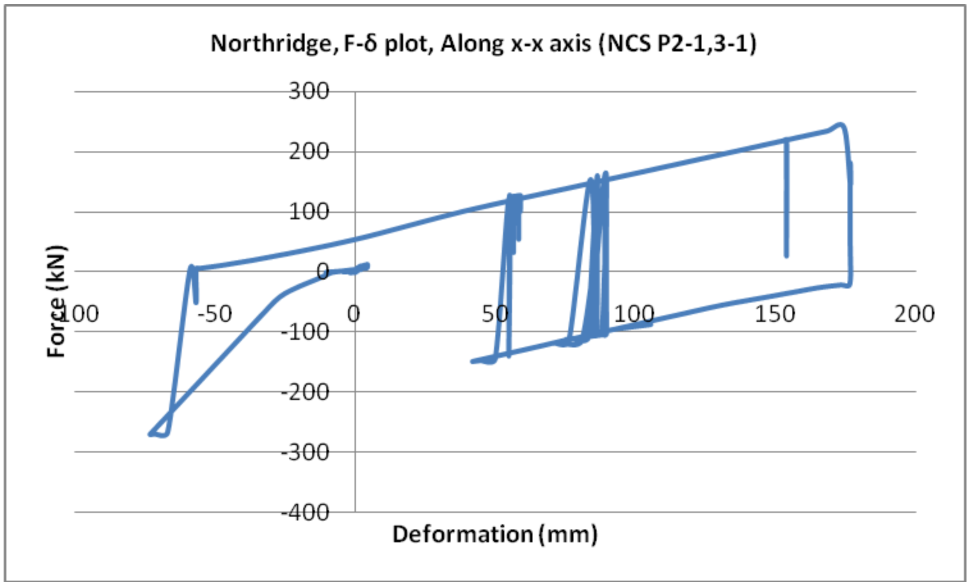

Charleston 2475, F-δ plot, Along y-y axis (NCS P1-1,1-2)
600
400
200
0
-200
-400
-600
-800
-1000
-300
-200
-100
0
100
200
300
400
500
Force (kN)
Deformation (mm)


Northridge, F-δ plot, Along x-x axis (NCS P1-1,1-2)
150
100
50
0
-50
-100
-150
-200
-200
-100
0
100
200
300
Force (kN)
Deformation (mm)

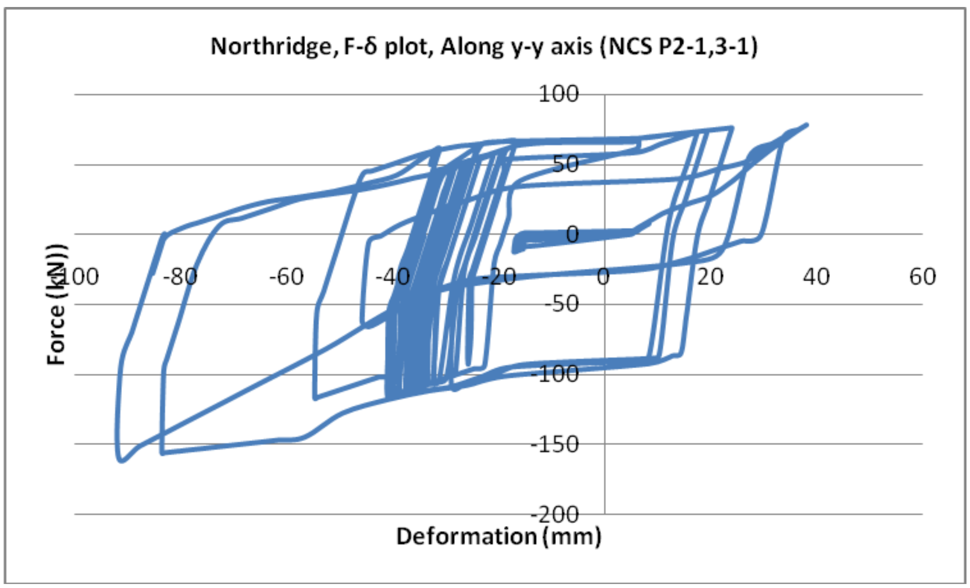

Northridge, F-δ plot, Along y-y axis (NCS P1-1,1-2)
200
150
100
50
0
-50
-100
-150
-200
-250
-100
-50
0
50
100
150
Force (kN)
Deformation (mm)


Charleston 2475, F-δ plot, Along x-x axis (NCS P2-1,3-1)
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-200
-100
0
100
200
300
Axis Title
Deformation (mm)

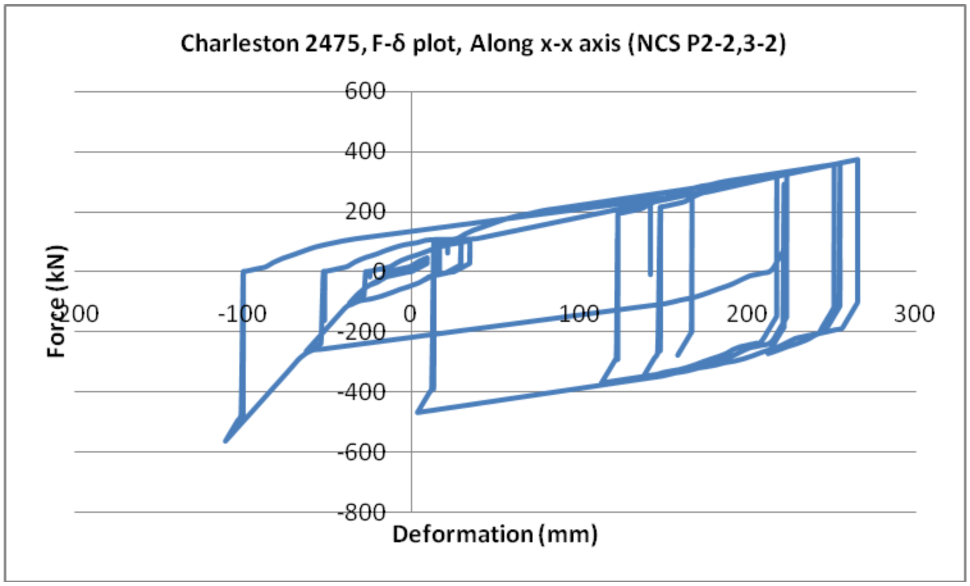

Charleston 2475, F-δ plot, Along y-y axis (NCS P2-1,3-1)
600
400
200
0
-200
-400
-600
-400
-300
-200
-100
0
100
200
300
Force (kN)
Deformation (mm)

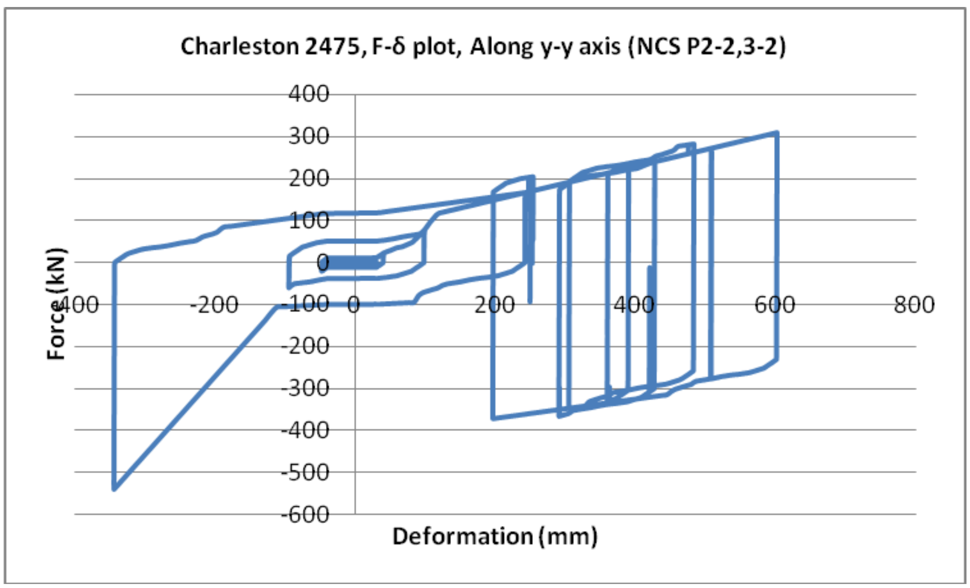


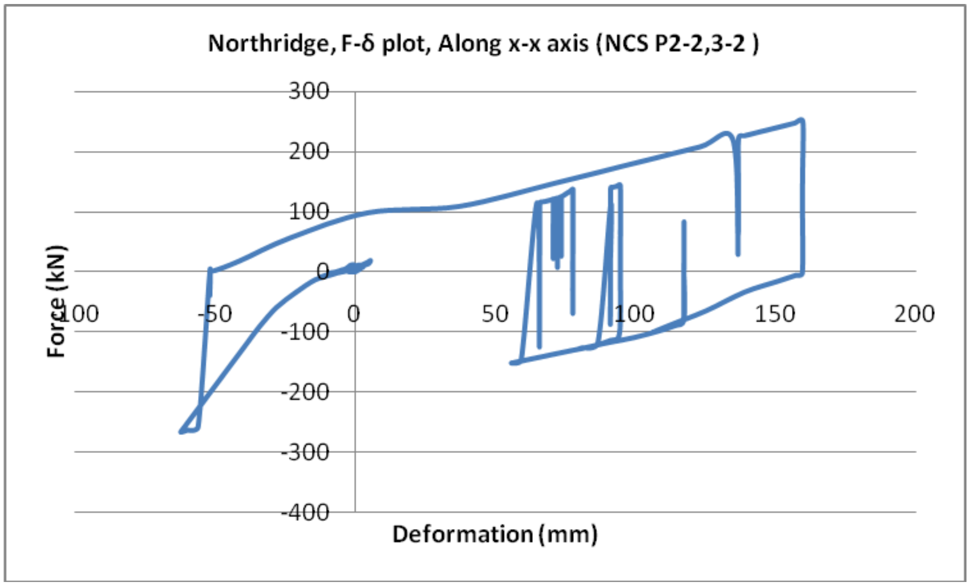
Northridge, F-δ plot, Along x-x axis (NCS P2-1,3-1)
300
200
100
0
-100
-200
-300
-400
-100
-50
0
50
100
150
200
Force (kN)
Deformation (mm)

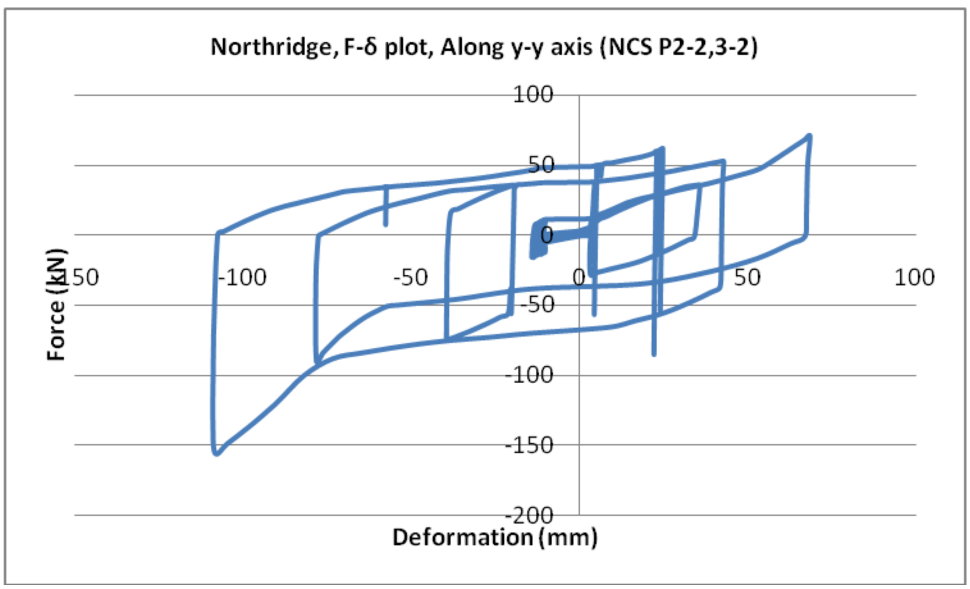


Northridge, F-δ plot, Along y-y axis (NCS P2-1,3-1)
100
50
0
-50
-100
-150
-200
-100
-80
-60
-40
-20
0
20
40
60
Force (kN))
Deformation (mm)


Charleston 2475, F-δ plot, Along x-x axis (NCS P2-2,3-2)
600
400
200
0
-200
-400
-600
-800
-200
-100
0
100
200
300
Force (kN)
Deformation (mm)


Charleston 2475, F-δ plot, Along y-y axis (NCS P2-2,3-2)
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-400
-200
0
200
400
600
800
Force (kN)
Deformation (mm)


Northridge, F-δ plot, Along x-x axis (NCS P2-2,3-2)
300
200
100
0
-100
-200
-300
-400
-100
-50
0
50
100
150
200
Force (kN)
Deformation (mm)


Northridge, F-δ plot, Along y-y axis (NCS P2-2,3-2)
100
50
0
-50
-100
-150
-200
-150
-100
-50
0
50
100
Force (kN)
Deformation (mm)

VITA

Siddharth Srivastava received his Bachelor of Technology degree in civil engineering from National Institute of Technology, Durgapur, India in 2007. He entered the structural engineering program in civil engineering at Texas A&M University in August 2007 and received his Master of Science degree in December 2008. His research interests include bridge engineering and structural dynamics.

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