EFFECT OF ISOLATORS ON REGULAR BRIDGES SUBJECTED TO SCALED NEAR FIELD AND FAR FIELD TIME HISTORIES

By

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ABSTRACT OF THE THESIS

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Seismic isolation is an important and widely used method to protect a structure from the devastating effects of earthquake ground motions. Seismic isolation seeks to mitigate the effects of the ground motions by decreasing the base shear acting on the structure by increasing the fundamental time period of the structure in question. This in turn affects the spectral acceleration and hence the base shear. This thesis deals with investigating the behavior of lead core rubber isolators, on bridges, under near field and far field earthquake loading. The earthquake records were scaled to three intensities, namely, very high, high, and medium to high. The parameters investigated were the longitudinal base shear, transverse base shear, longitudinal displacement and transverse displacement caused by a wide range of scaled earthquake load intensities. SAP 2000 was used to run the analysis on different bridge models which varied in the number of spans, length of span and the height of the columns. The lead core rubber isolators used in the models varied in the longitudinal and transverse stiffness. The isolator stiffness ranged from 90 kips per feet to 270 kips per feet. The results showed that the isolators reduced the longitudinal base shear for most cases. With the use of isolators there was also an

increase in displacements. The results in the transverse direction showed variability which was caused by not smoothing out the response curves for the ground motions in the transverse direction. The results also show that care has to be taken when using isolation for bridges in locations with very high intensity earthquakes. For medium to high intensity earthquakes, isolators with initial stiffness between 90 to 270 k/ft can be used. For bridges in extreme earthquake zones, the use of isolators should be evaluated based on the earthquake record used and the bridge properties. The results also show that using isolators for bridges with less flexible substructure resulted in a greater reduction in base shear for most cases. The use of isolators with high initial stiffness, resulted in lower base shears in far field cases when compared to near field cases.

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I would like to firstly thank Dr. Husam Najm for being my thesis advisor and for his immense patience, guidance and support with my research. I would like to also thank my committee members Dr. Balaguru and Dr. Yong for their guidance and support. I would like to thank my father, my mother and my brother for believing in me and being a constant and unwavering source of support throughout my course of study. I would also like to thank my friends Parameshwar Reddy, Srikant Viswanath, and Aditya Mantha for all the lighter moments we shared that helped me going.

DEDICATION

I would like to dedicate this thesis to my father Madan Mohan, my mother Yasodhara and my brother Karthik.

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CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

Seismic isolation is an old design idea which proposes decoupling of a structure or part of it, or even of equipment placed in the structure, from the damaging effects of ground accelerations. One of the goals of seismic isolation is to shift the fundamental frequency of a structure away from the dominant frequencies of earthquake ground motion and fundamental frequency of the fixed base superstructure to reduce ground accelerations acting on the structure.

The other purpose of an isolation system is to provide an additional means of energy dissipation through additional damping, thereby reducing the transmitted acceleration into the superstructure. This innovative design approach aims mainly at the isolation of a structure from the supporting ground, generally in the horizontal direction, in order to reduce the transmission of the earthquake motion to the structure. A variety of isolation devices including elastomeric bearings (with and without lead core), frictional/sliding bearings and roller bearings have been developed and used practically for aseismic design of buildings during last 20 years in many new buildings in countries like USA, Japan, UK, Italy, New Zealand and others. The detailed review of earlier and recent works on base isolation systems and their applications to buildings has been widely reported.

Bridges are lifeline structures. They act as an important link in surface transportation network and failure of bridges during a seismic event will seriously hamper the relief and rehabilitation work. There are many cases of damage of bridges in the past earthquakes all over the world. Due to their structural simplicity, bridges are particularly vulnerable to damage and even collapse when subjected to earthquakes.

The fundamental period of vibration of a majority of regular bridges is in the range of 0.2 to 1.2 second. In this range, the structural response is high because it is close to the predominant periods of earthquake-induced ground motions. For very rigid structures like normal bridges with short piers and abutments the time period is often extremely small. For such structures the response is almost the same as the ground acceleration. The seismic forces on the bridges can be reduced if the fundamental period of the bridge is lengthened or the energy dissipating capability is increased. Therefore, seismic isolation is an effective and promising mitigating measure for earthquake-resistant design of bridges.

Considerable efforts have been made to develop improved seismic isolation design procedure for new bridges and comprehensive retrofit guidelines for existing bridges. The suitability of a particular arrangement and type of isolation system will depend on many factors including the span, number of continuous spans, seismicity of the region, frequencies of vibration of the relatively severe components of the earthquake, maintenance and replacement facilities.

Disadvantages of base isolation systems include their vulnerability to strong pulse-type ground motions generated at near-fault zones. The complementary damping provided by the base isolation may in certain cases induce energy into the higher modes of vibration and increase member deformations and accelerations of an isolated structure resulting in subsequent structural and nonstructural damages. Another potential disadvantage of isolation bearings is continuous maintenance to make sure that they will perform as designed during a seismic event.

Examples of base isolated structures include the Los Angeles City Hall, Foothill Law, and the Justice Center in Los Angeles, California. The Bai-Ho Bridge that spans across the Gia-Nan canal in Taiwan utilizes an LCR (Lead Core Rubber) isolation device, and the Yama-age Bridge in Japan employs a high-damping-rubber bearing dissipation system. The Marga-Marga Bridge in Vina del Mar, which is located in a high seismic risk area in Chile, is protected using high-damping rubber bearings. Following the Great Hanshin/Awaji earthquake (also referred to as the Hyogo-Ken Nanbu, or Kobe earthquake) on January 17, 1995, the Benten Viaduct Highway Bridge in Kobe City, Japan was rebuilt in 18 months using LCR isolation.

Such catastrophes and structural failures have motivated researchers to develop effective damage mitigation systems to protect various types of structures. Base isolation has become a conventional method for protecting buildings and bridges from seismic events. It has been used to prevent brittle failure in piers, to reduce the spectral accelerations in stiff piers, and to reduce the shear force at the bases of bridges.

Nowadays, isolation bearings are considered as an attractive method to reduce earthquake-induced accelerations in structures. Researchers have conducted several experimental studies on the use of sliding disc bearings and rubber restoring force devices to isolate bridge models under various types of ground motion excitations. The results showed that these devices resulted in significantly smaller responses than non-isolated bridges. Tsopelas et al. [1996] performed analytical and experimental studies of elasto-plastic isolated systems and concluded that these systems are vulnerable to shock-type seismic motions that result in large displacement demands. Over the last two decades, LCR isolators have been integrated into various buildings and bridges because of their large energy dissipation capability (via their large hysteresis region) and because of their attractive physical compactness and ease of installation and inspection.
[This section has been adopted from Jangid and Kunde, 2003]

1.2 SEISMIC ISOLATION SYSTEMS

There are basically two types of isolation systems, namely sliding bearings and elastomeric bearings. Elastomeric bearings have low horizontal stiffness and they shift the fundamental time period of structures so that resonance due to the excitations caused by the ground motions does not occur. Sliding bearings work based on the principle of sliding friction.

An isolation system should have the capability to dissipate energy, provide additional horizontal flexibility and support the structure, and perform these three operations at the same time. The parameters to be considered while choosing an isolation system are the following:

1) Shifting the fundamental time period of the structure.
2) Adding Damping to the structure.
3) Initial stiffness.
4) Vertical stiffness.
5) Yielding force and displacement.
6) Energy dissipation or hysteresis behavior

1.2.1 ELASTOMERIC BEARINGS

The most commonly used elastomeric bearing is the laminated rubber isolator bearing (LRB). The basic components of this type of bearing are rubber and steel plates built in alternate layers. The LRB system shows high vertical stiffness, damping capacity and horizontal flexibility. The isolation system operates by isolating the superstructure from the horizontal components of ground motion by introducing a layer of low horizontal stiffness between the superstructure and the foundation. The isolation effects in this type of system are produced not by absorbing the earthquake energy but by deflecting through the dynamics of the system. (Kelly, 1997). These systems are resilient to adverse environmental conditions and quite easy to manufacture.

The second type of elastomeric bearings are the Lead Core Rubber (LCR) Isolation bearings. The characteristic component of this bearing system is the lead core. This component has a very high stiffness which helps the bearing system to take high axial loads and also provides an additional means of energy dissipation. The LCR isolation system offers axial load support, flexibility in the horizontal direction, damping and restoring force. The energy absorbing capability of the lead core leads to a decrease in the lateral displacement of the isolator. Presently the LCR Isolation bearing has overtaken the LRB Isolation bearing in usage, to become the most widely used isolation system. Fig. 1-1 shows details of the lead core rubber bearing. Table 1-1 adopted from DIS shows properties of the most commonly used LRB bearings and their range of application.

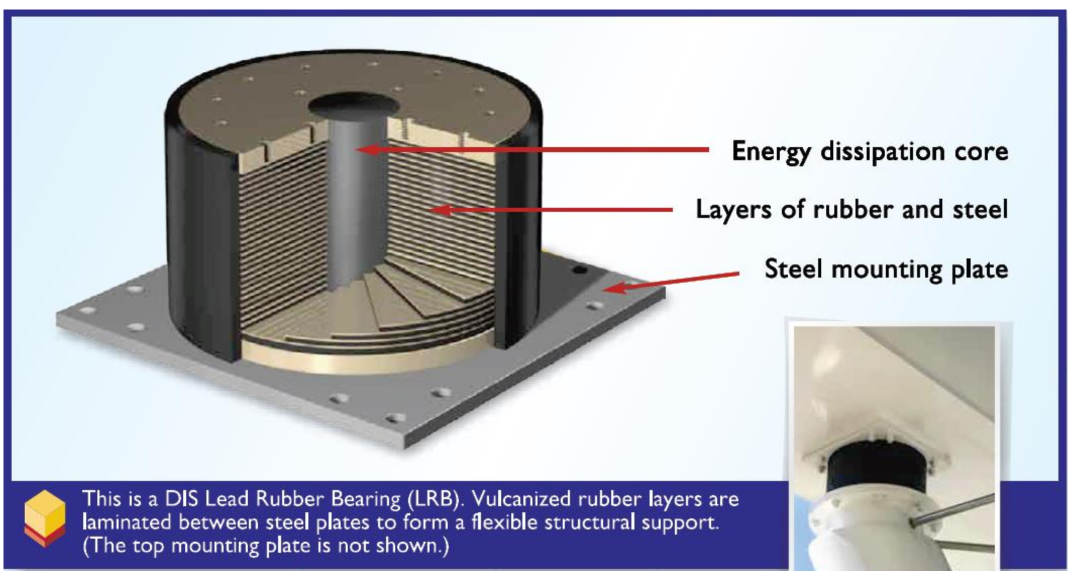


Fig. 1-1 Lead core rubber bearing details (DIS, 2007)

Table 1-1. Properties of LRB and their range of application (Dis 2007)

Isolator Diameter, D_I (in)	DESIGN PROPERTIES			Maximum Displacement, D_{max}(in)	Axial Load Capacity, P_{max}(kips)
	Yielded Stiffness, K_d(k/in)	Characteristic Strength, Q_d(kips)	Compression Stiffness, K_v(k/in)		
12.0	1-2	0-15	>250	6	100
14.0	1-2	0-15	>500	6	150
16.0	2-3	0-25	>500	8	200
18.0	2-4	0-25	>500	10	250
20.5	2-4	0-40	>1,000	12	300
22.5	3-5	0-40	>3,000	14	400
25.5	3-6	0-50	>4,000	16	600
27.5	3-8	0-50	>4,500	18	700
29.5	4-9	0-60	>5,000	18	800
31.5	4-9	0-60	>6,000	20	900
33.5	4-10	0-80	>7,000	22	1,100
35.5	4-11	0-80	>8,000	22	1,300
37.5	4-12	0-110	>10,000	24	1,500
39.5	5-12	0-110	>11,000	26	1,700
41.5	5-12	0-130	>12,000	28	1,900
45.5	6-12	0-150	>16,000	30	3,100
49.5	7-13	0-170	>21,000	32	4,600
53.5	8-14	0-200	>29,000	34	6,200
57.1	9-14	0-230	>30,000	36	7,500
61.0	10-14	0-230	>37,000	36	9,000

1.2.2 SLIDING ISOLATION SYSTEMS

Sliding isolation systems are a popular and effective technique of seismic isolation. They perform very well under various types of extreme earthquake load cases. They are quite effective in their reduction of the superstructure's acceleration. These isolators remain independent of the frequency of earthquake excitations, due to its propensity for reduction and spreading of the earthquake energy over a large range of frequencies. The sliding isolation systems can be used both for buildings as well as bridges.

The concept of sliding bearings has been combined with the concept of a pendulum type response, bringing about a new type of isolation system called the Friction Pendulum System (FPS). In this system isolation is achieved by means of an articulated slider on a spherical chrome surface. The slider is faced with a bearing material which when in contact with the polished chrome surface, results in a maximum sliding friction coefficient of the order of 0.1 (Jangid and Kunde, 2003). Fig. 1-2 shows the details of the of FPS type bearings.

The system starts acting when the earthquake forces overcome the static friction value. Once it begins to act, it develops a force which is equal to the summation of the frictional force and restoring force. Isolation is achieved in the same way as in Elastomeric bearing systems, i.e. by shifting the natural period of vibration of the structure. The natural period is governed by the radius of curvature of the concave surface.

[This section has been adopted from Jangid and Kunde, 2003]

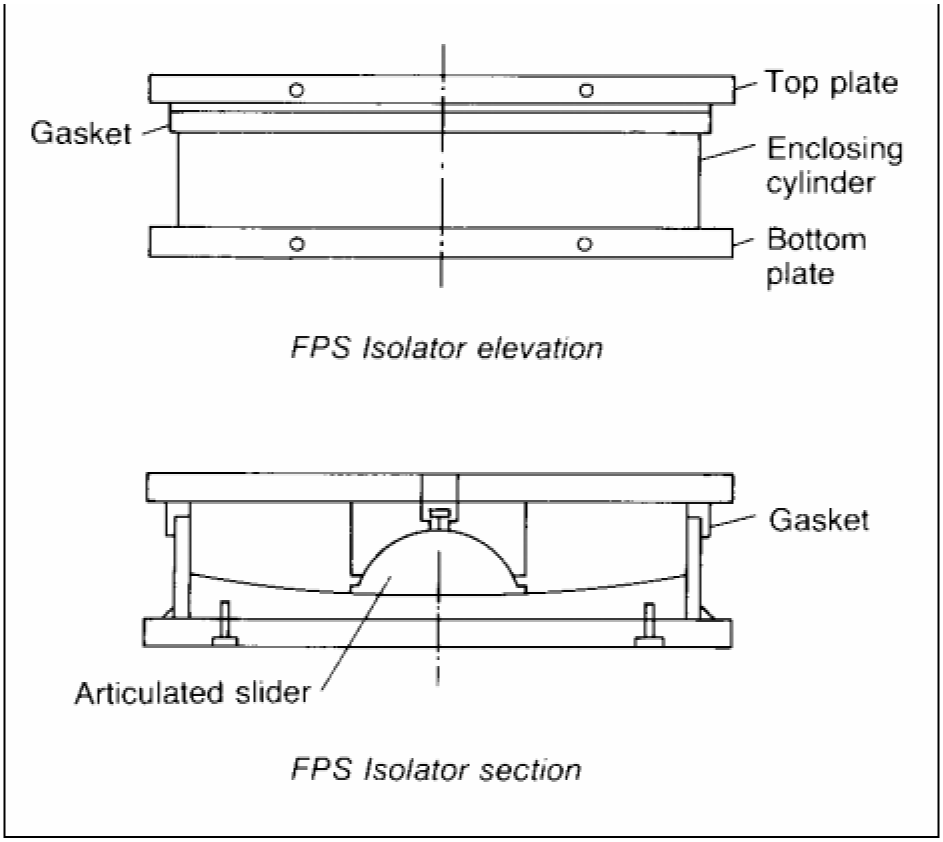


Fig. 1-2 Details of FPS Isolation bearing (Jangid, et al., 2003)

1.3 APPLICATIONS OF SEISMIC ISOLATION SYSTEMS

Seismic isolation has been implemented in several new bridges and in existing bridges as well in buildings. The decision on whether to use seismic isolation to mitigate the effects of earthquake ground motions depends on several factors. These factors include the earthquake intensity, structure use, architectural considerations, cost, and others.

GOLDEN GATE BRIDGE SEISMIC RETROFIT CONSTRUCTION PROJECT

The Golden Gate Bridge spans the Golden Gate Strait linking the City of San Francisco and the counties to the north. Serving up to 40 million vehicles a year, it serves a vital transportation link for the San Francisco Bay Area. The Bridge is operated by a special district of the State of California formed in 1928. This special district, the Golden Gate Bridge, Highway and Transportation District (GGBHTD), expanded its mission to include the operation of Golden Gate Transit bus system in 1971/1972 and the Golden Gate Ferry system in 1970. Spanning 1.7 miles from abutment to abutment, the Golden Gate Bridge is made up of six structures:

1. San Francisco (south) Approach Viaduct
2. San Francisco (south) Anchorage Housing and Pylons S1 and S2
3. Fort Point Arch
4. Main Suspension Bridge
5. Marin (north) Approach Viaduct
6. Marin (north) Anchorage Housing and Pylons N1 and N2

LOMA PRIETA EARTHQUAKE, October 17, 1989

It was a bone rattling, concrete crushing, nerve-racking 15 seconds. At 5:04 p.m. on Tuesday evening, October 17, 1989, the 7.1 magnitude Loma Prieta earthquake caused 68 deaths, at least 3,700 injuries and an estimated dollar loss of $6 billion to $7 billion. The earthquake reminded the world that the San Francisco Bay region remains vulnerable. Although the Golden Gate Bridge suffered no observed damage from the Loma Prieta quake, since the epicenter was located some 60 miles to the south, the earthquake became a catalyst for the extensive seismic retrofit program that the historic structure is undergoing today.

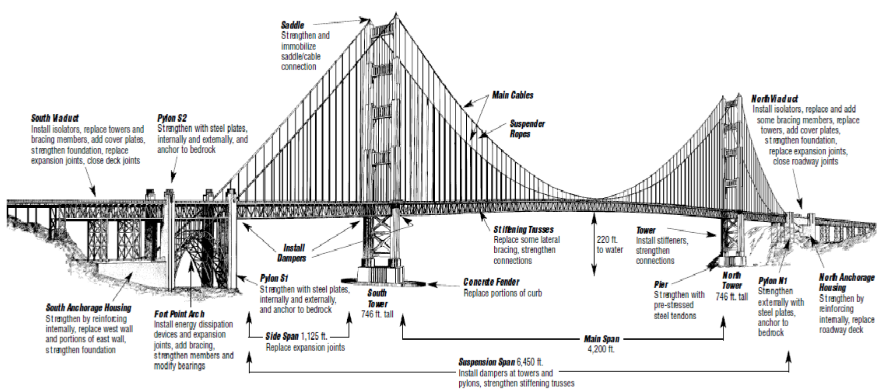
Perhaps the most impressive statistic resulting from research conducted since the Loma Prieta earthquake is the conclusion by the U.S. Geological Survey (USGS) and other scientific organizations that there is a 62% probability of at least one magnitude 6.7 or greater quake capable of causing widespread damage, impacting the San Francisco Bay region before 2031.

Immediately following the Loma Prieta quake, the GGBHTD engaged a team of consultants to conduct a vulnerability study. The conclusion of the study was that under a Richter magnitude 7.0 or greater earthquake with an epicenter near the Bridge, it would experience severe damage that could close this important transportation link for an extended period. If a Richter magnitude 8.0 or greater earthquake centered near the Bridge, there would be a substantial risk of impending collapse of the San Francisco and Marin Approach Viaducts and the Fort Point Arch, and extensive damage to the remaining Bridge structures, including the Main Suspension Bridge. It must be noted, that as of July 2008 with the completion of the second phase of construction, the seismic retrofit of the Golden Gate Bridge is far enough along that the Bridge no longer faces the potential for collapse and until the entire retrofit is completed, the risk of significant damage to the Main Suspension Bridge remains.

After determining that retrofitting the Bridge would be more cost-effective than replacing it, in 1992, the District hired engineering consultants to develop seismic retrofit design criteria. As part of this task, the site-specific design ground motions associated with different magnitudes of earthquakes and expected performance levels were defined as the basis for the Bridge retrofit design. The site-specific, moderate earthquake was defined as one having a 10 percent chance of being exceeded in a 50-year period or having an acceleration of 0.46g. The site-specific, maximum credible earthquake was defined as one having a return period of 1,000 years or having an acceleration of 0.65g, which is equivalent to the 1906 San Francisco earthquake of a magnitude 8.3 on the Richter scale.

Because of financial constraints, the District proceeded with phasing the construction of the seismic retrofit in a manner that reflected the degrees of structural vulnerabilities. In 1996, the three construction phases were established as follows:

- Phase 1: Retrofit the Marin (north) Approach Viaduct
- Phase 2: Retrofit the San Francisco (south) Approach Viaduct, San Francisco (south) Anchorage Housing, Fort Point Arch, and Pylons S1 and S2
- Phase 3A and 3B: Retrofit the Main Suspension Bridge and Marin (north) Anchorage Housing



SEISMIC RETROFIT MEASURES

Fig. 1-3 Seismic retrofit measures for the Golden Gate Bridge. (Overview of Golden Gate Bridge Seismic Retrofit Construction Project, 2013)

[This section has been taken from www.goldengatebridge.org/projects/retrofit.php]

CHAPTER TWO MODEL DESCRIPTION AND ANALYTICAL INVESTIGATION

2.1 SIMULATION MODEL

A basic bridge model was created to investigate the effect of isolators on bridge response under earthquake ground motions. The basic model was comprised of two continuous spans with an intermediate pier. The span ends were supported on rollers. The top of the pier was fixed (girder and column are constrained together but rotation is different for each member). The simulation model was created using SAP2000 v.15. Initially the program Csi Bridge was used to create the model. The Csi Bridge has 3-D capabilities and can model individual girders and the deck using solid elements. . However, it was not clear in the program documentation how the support conditions and interface locations are modeled. In addition, the program lacked flexibility that allowed the user to introduce multiple bearing systems and other components of the structure. Since most of bridges are regular bridges, modeling bridges using beam frame models was sufficient for this investigation. Bridges with variable cross-sections and bridges with tight curvature were not a part of this study. In addition SAP2000 can perform linear and nonlinear analysis using response spectrum analysis and time history analysis. Various variations of the basic model were created. They include variable spans, variable length, variable column heights, variable isolator properties and various earthquake ground motions. A summary of the parameters investigated in this study are given in Tables 2-5 and 2-6.

The deck frame has the following properties:

Table 2-1 Deck Properties

Cross sectional Area (Axial)	79.1184 sq.ft.
Moment of Inertia about 3-3 axis	437.1949 ft^4
Moment of Inertia about 2-2 axis	11957.667 ft^4
Shear area in 2-2 direction	40 sq.ft.
Shear area in 3-3 direction	40 sq.ft.

The column is circular in cross section with a diameter of 7 feet. The column is fixed at the bottom and pin connected to the deck. The bearing (isolator) was placed at the top of the column to support the deck. The bearing depth varied from 12in to 24in. Two column heights were considered in this analysis: 25 feet and 50 feet.

The support conditions of the deck are as follows:

Table 2-2 Support Conditions

Support	Restraints
Right Support	U2, U3, R1, R3
Left Support	U2, U3

At both ends springs with a stiffness of 15,000 kips/ft. in the transverse direction have been provided to simulate abutments.

The bearings are provided at the top of the columns. The bearings are 2 feet long and are modelled as rubber isolators with the following properties:

Table 2-3 Properties of Rubber Isolators

Direction	Effective Stiffness (Kips per ft.)
U1	1,000,000
U2	90
	180
	270
U3	90
	180
	270

The effective stiffness of the bearing in the U1 direction has to be 100-10,000 times the stiffness of the column, hence 1,000,000 kips/ft. was chosen. The typical range of time period of an isolated bridge is between 3-6 seconds, hence 90 and 270 kips/ft. were chosen as limits of the isolator stiffness to be considered after performing multiple trials.

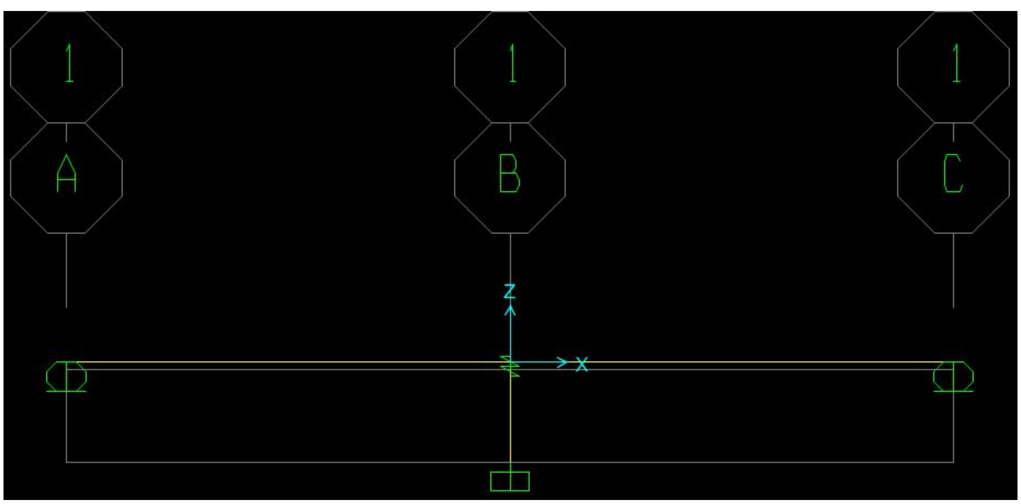


Fig. 2-1 Line model of the two span bridge with a 25 feet long column.

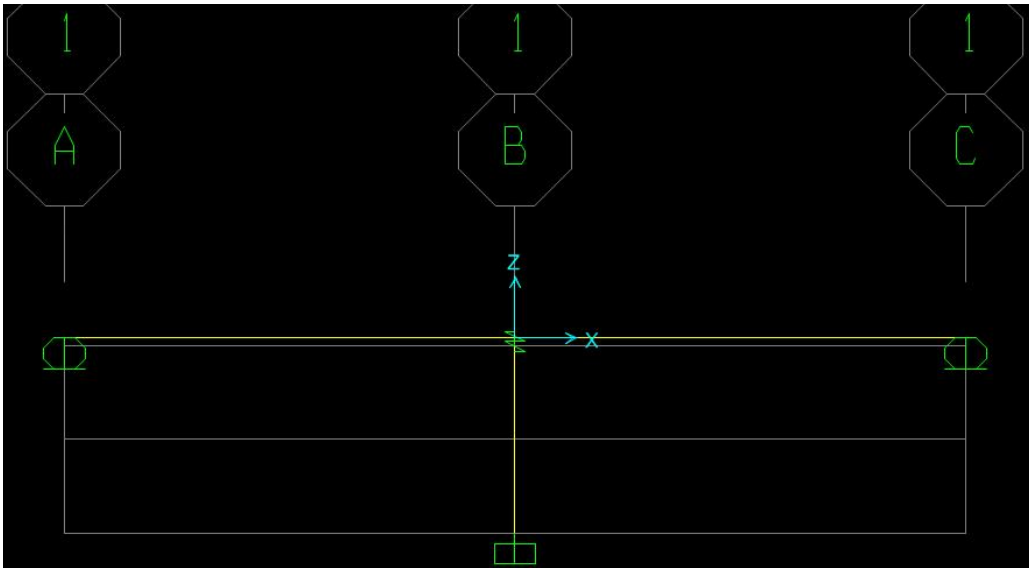


Fig. 2-2 Line model of the two span bridge with a 50 feet long column.

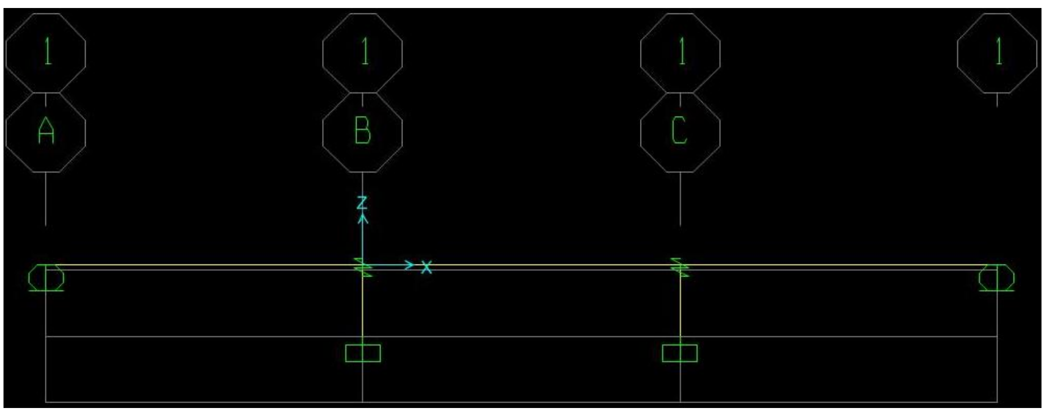


Fig. 2-3 Line model of the three span bridge with three equal spans of 120 feet, with a 25 feet long column.

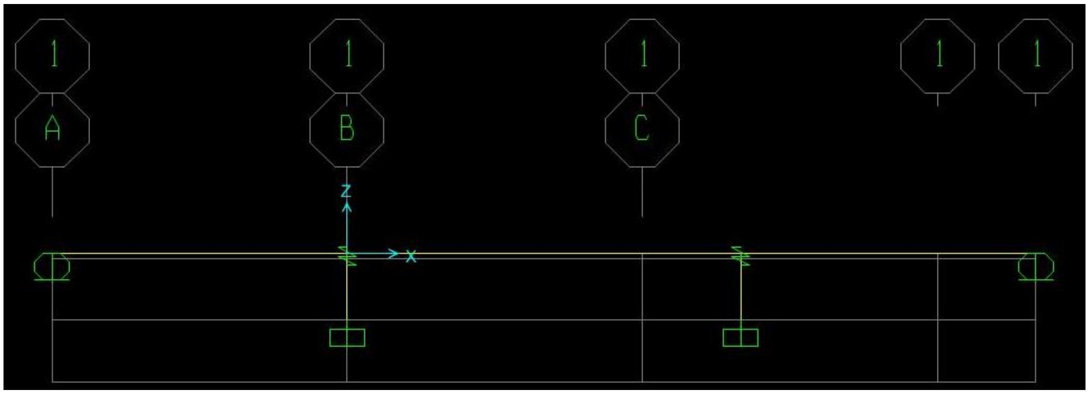


Fig. 2-4 Line model of the three span bridge with span lengths of 120 feet, 160 feet and 120 feet, with a 25 feet long column.

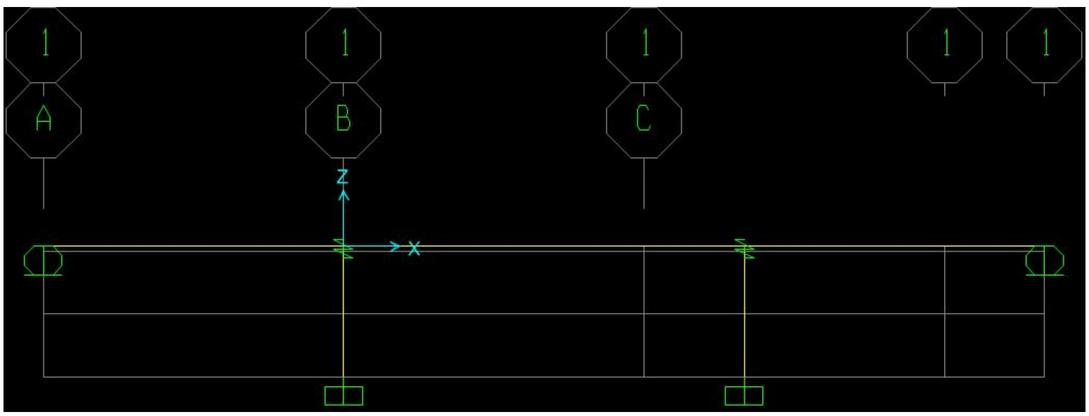


Fig. 2-5 Line model of the three span bridge with span lengths of 120 feet, 160 feet and 120 feet, with a 50 feet long column.

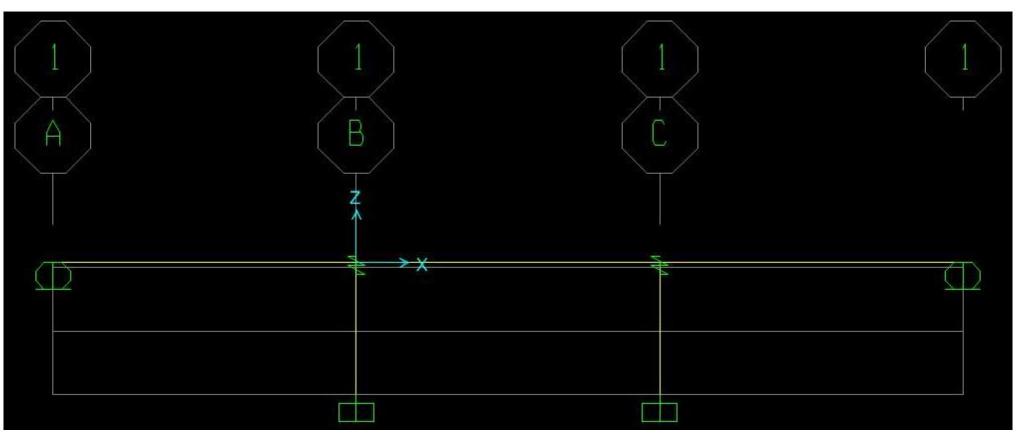


Fig. 2-6 Line model of the three span bridge with three equal spans of 120 feet, with a 50 feet long column.

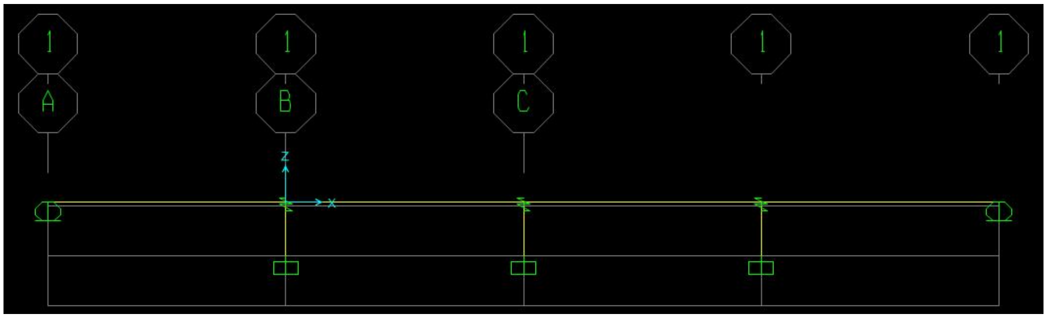


Fig. 2-7 Line model of the four span bridge with four equal spans of 120 feet, with a 25 feet long column.

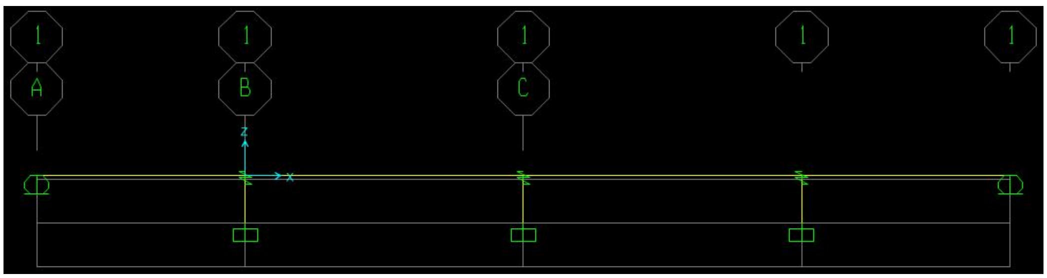


Fig. 2-8 Line model of the four span bridge with span lengths of 120 feet, 160 feet, 160 feet and 120 feet, with a 25 feet long column.

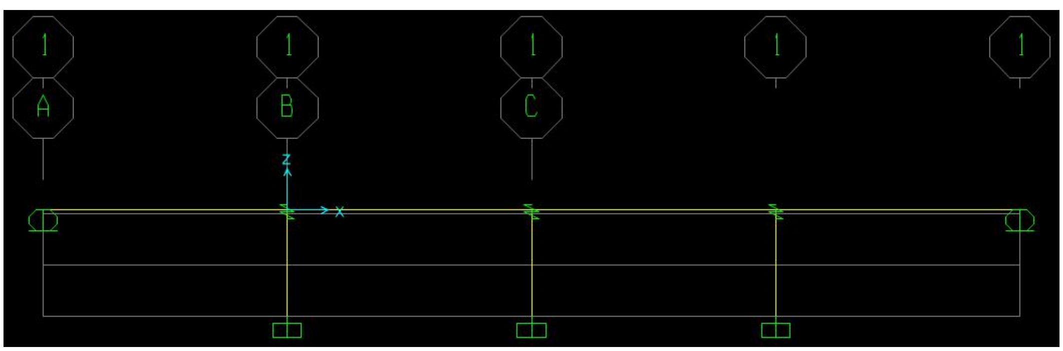


Fig. 2-9 Line model of the four span bridge with four equal spans of 120 feet, with a 50 feet long column.

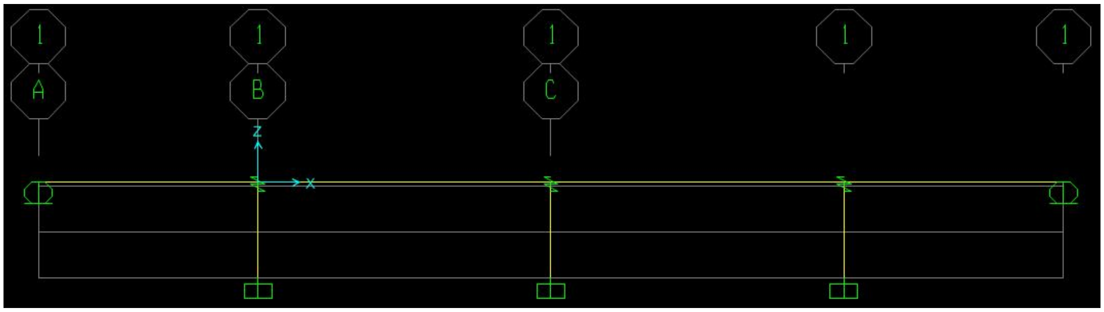


Fig. 2-10 Line model of the four span bridge with span lengths of 120 feet, 160 feet, 160 feet and 120 feet, with a 50 feet long column.

2.2 MODEL PARAMETERS AND METHODS OF EVALUATION

2.2.1 EARTHQUAKE GROUND MOTIONS

The following criteria were used for selecting Near Field earthquakes:

- The closest distance to rupture(R) is less than 10 km.
- Magnitude: 6.5-7.9
- Fault distance: 1.7 km – 8.8 km.
- PGA: 0.22g-1.43g
- PGV: 30cm/sec.-167cm/sec.

The following criteria were used for selecting Far Field earthquakes:

- The closest distance to rupture(R) is greater than 10 km.
- Magnitude: 6.5-7.6
- Fault distance: 11.1 km – 26.4 km.
- PGA: 0.21g – 0.82g
- PGV: 19 cm/sec. -115 cm/sec. (Kircher, Haselton 2007)

Table 2-4 Earthquake Magnitudes

Record Sequence Number	Earthquake Name	Year	Station Name	Magnitude
125	Friuli, Italy-01	1976	Tolmezzo	6.50
161	Imperial Valley-06	1979	Brawley Airport	6.53
169	Imperial Valley-06	1979	Delta	6.53
170	Imperial Valley-06	1979	EC County Center FF	6.53
179	Imperial Valley-06	1979	El Centro Array #4	6.53
180	Imperial Valley-06	1979	El Centro Array #5	6.53
183	Imperial Valley-06	1979	El Centro Array #8	6.53
752	Loma Prieta	1989	Capitola	6.93
802	Loma Prieta	1989	Saratoga - Aloha Ave	6.93
827	Cape Mendocino	1992	Fortuna - Fortuna Blvd	7.01
864	Landers	1992	Joshua Tree	7.28
879	Landers	1992	Lucerne	7.28
960	Northridge-01	1994	Canyon Country - W Lost Canyon	6.69
1044	Northridge-01	1994	Newhall - Fire Sta	6.69
1050	Northridge-01	1994	Pacoima Dam (downstr)	6.69
1051	Northridge-01	1994	Pacoima Dam (upper left)	6.69
1086	Northridge-01	1994	Sylmar - Olive View Med FF	6.69
1116	Kobe, Japan	1995	Shin-Osaka	6.90
1158	Kocaeli, Turkey	1999	Duzce	7.51
1246	Chi-Chi, Taiwan	1999	CHY104	7.62
1489	Chi-Chi, Taiwan	1999	TCU049	7.62
1493	Chi-Chi, Taiwan	1999	TCU053	7.62
1494	Chi-Chi, Taiwan	1999	TCU054	7.62
1602	Duzce, Turkey	1999	Bolu	7.14
1787	Hector Mine	1999	Hector	7.13

2.2.2 ISOLATOR PROPERTIES

Table 2-5 Isolator Properties

Limits of Isolator Stiffness	Isolator stiffnesses(Kips per feet)
Lower Limit	90
Midpoint Limit	180
Upper Limit	270

2.2.3 BRIDGE PROPERTIES

Table 2-6 Properties of the Bridge model

Type of Bridge	No. of Spans	Span Length(feet)	Column height(feet)
Two Span	2	120-120	25
Two Span L.C	2	120-120	50
Three Span-360	3	120-120-120	25
Three Span L.C-360	3	120-120-120	50
Three Span-400	3	120-160-120	25
Three Span L.C-400	3	120-160-120	50
Four Span-480	4	120-120-120-120	25
Four Span L.C-400	4	120-120-120-120	50
Four Span-560	4	120-160-160-120	25
Four Span L.C-560	4	120-160-160-120	50

2.3 SCALING OF EARTHQUAKE RECORDS

The AASHTO LRFD Bridge Design Specifications (AASHTO, 2010b) includes guidelines on scaling earthquake records for use in the analysis and design of bridges. The guidelines include mandatory language and commentary related to "…step-by-step time history method of analysis used for either elastic or inelastic analysis…" Article 4.7.4.3b of the specification requires that the scaled ground motions have the same characteristics as the unscaled ground motions. It also requires to use the maximum scaled ground motion from three records and the mean scaled ground motion if a minimum of seven records are used. "Developed time histories shall have characteristics that are representative of the seismic environment of the site and the local site conditions. Response-spectrum-compatible time histories shall be used as developed from representative recorded motions. Analytical techniques used for spectrum matching shall be demonstrated to be capable of achieving seismologically realistic time series that are similar to the time series of the initial time histories selected for spectrum matching. Where recorded time histories are used, they shall be scaled to the approximate level of the design response spectrum in the period range of significance. Each time history shall be modified to be response-spectrum-compatible using the time-domain procedure. At least three response-spectrum-compatible time histories shall be used for each component of motion in representing the design earthquake (ground motions having a seven percent probability of exceedance in 75 years). All three orthogonal components (x, y and z) of design motion shall be input simultaneously when conducting a nonlinear time-history analysis. The design actions shall be taken as the maximum response calculated for the three ground motions in each principal direction. If a minimum of seven time histories are used for each component of motion, the design actions may be taken as the mean response calculated for each principal direction. For near-field sites (D < 6 mi), the recorded horizontal components of motion that are selected should represent a near-field condition and should be transformed into principal components before making them response-spectrum compatible. The major principal component should then be used to represent motion in the fault-normal direction and the minor principal component should be used to represent motion in the fault-parallel direction". The AASHTO requirements are specified for analysis and design and they should be followed when designing bridges in the United States.

In this study, the focus was on the performance of isolators and a total of 50 ground motion acceleration records were evaluated in this study. Twenty-eight (28) records were Near Field (NF) and twenty two (22) records were Far Field. The 28 Near Field and 22 Far Field earthquake records were scaled using the PEER Ground Motion Database (PGMD) and the program SeismoSignal. The PGMD was used to scale the records to a specific target spectrum and get the scale factors for each individual earthquakes. SeismoSignal was then used to generate the scaled earthquake records using the corresponding scale factors determined using the PGMD. The earthquake records were scaled to 3 intensities: medium to high (I), high (II), and very high (III).

The procedure for generating scale factors for the earthquakes in PGMD is as follows:

Choose the type of Target Spectrum. There are 3 options, which are the PEER-NGA spectrum, User defined spectrum and ASCE code spectrum. The ASCE code spectrum was used to scale the earthquake records. To generate the ASCE code spectrum, three parameters are needed, they are the Sds, Sd1, and TL values. Sds is the design Spectral acceleration parameter at short period, Sd1 is the design Spectral acceleration at 1 second period and TL is Long-period transition period. Sds and Sd1 are calculated as follows:

Sds = Fa*Ss

Sd1 = Fv*S1

Fa and Fv are site coefficients and Ss and S1 are the site specific short and one period spectral accelerations respectively. The soil is assumed to be rock soil (Site class B), hence Fa=Fv=1. The Ss and S1 values for very high, high and medium to high scales are as follows:

Very high	Ss = 2.0g, S1 = 0.7g.
High	Ss = 1.0g, S1 = 0.25g.
Medium to high	Ss = 0.5g, S1 = 0.15g.

Since Fa=Fv=1, Sds = Ss and Sd1 = S1. TL is taken to be 6 seconds. Once the three required values are entered, we can generate the target spectrum. After it has been generated, the next step is to select the earthquakes to be scaled. 14 near field and 11 far field earthquakes (with 2 components) are chosen and then scaled to the target spectrum, to generate the scale factors for each earthquake.

Once the scale factors are obtained from the PGMD, they are used in the SeismoSignal software to generate scaled earthquake records. The procedure for generating scaled earthquake records is as follows:

The earthquake record to be scaled is selected, the appropriate time step is chosen and uploaded into the software. The scale factor is given as an input and then the record is scaled. The scaled record is then saved and is used in the analysis program (SAP2000) as an input for seismic analysis.

Steps for generating scaled earthquake ground motion:

1. Generating the Target Spectrum: The first step is to select a target or design spectrum. The target spectrum can be obtained from the corresponding design codes. For bridge design, the AASHTO LRFD design spectrum was used as shown in Fig. 2-11

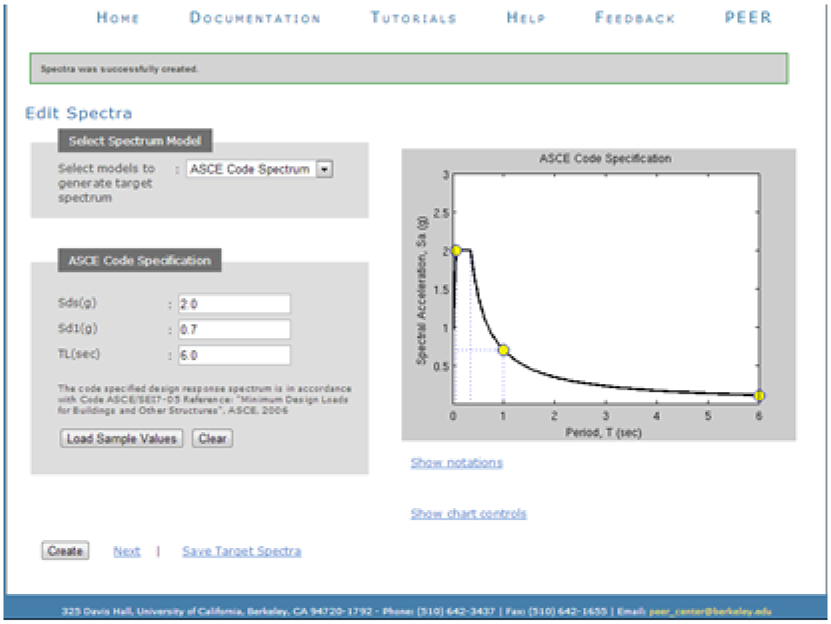


Fig. 2-11 AASHTO design spectrum for high earthquake intesity.

2. Use PGMD to obtain the scale factor for the desired earthquake record. Fig. 2-12 shows the list of scaled earthquake records generated, along with the scale factors which were used to generate them.

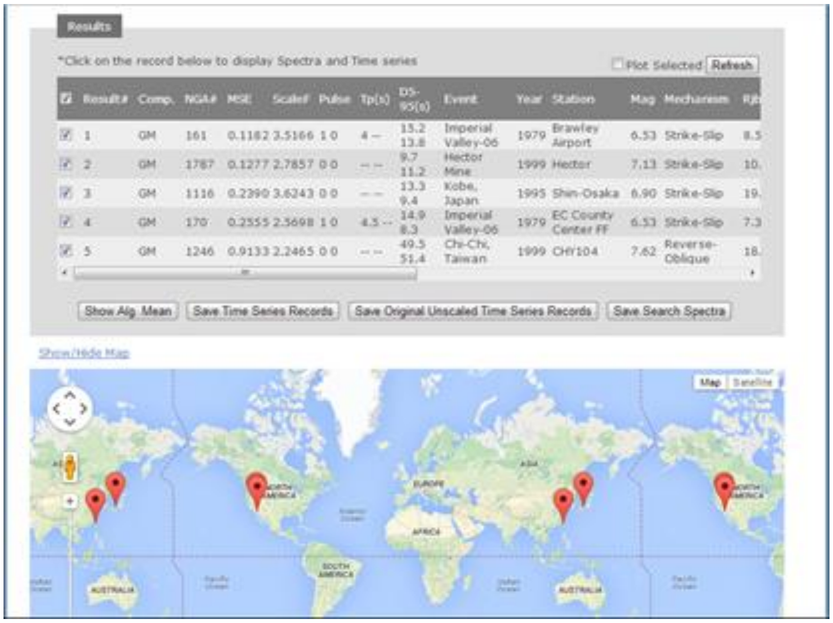


Fig. 2-12 List of scale factors with the scaled earthquake records.

Fig. 2-13 shows the target spectrum compared to other spectra from PMGD

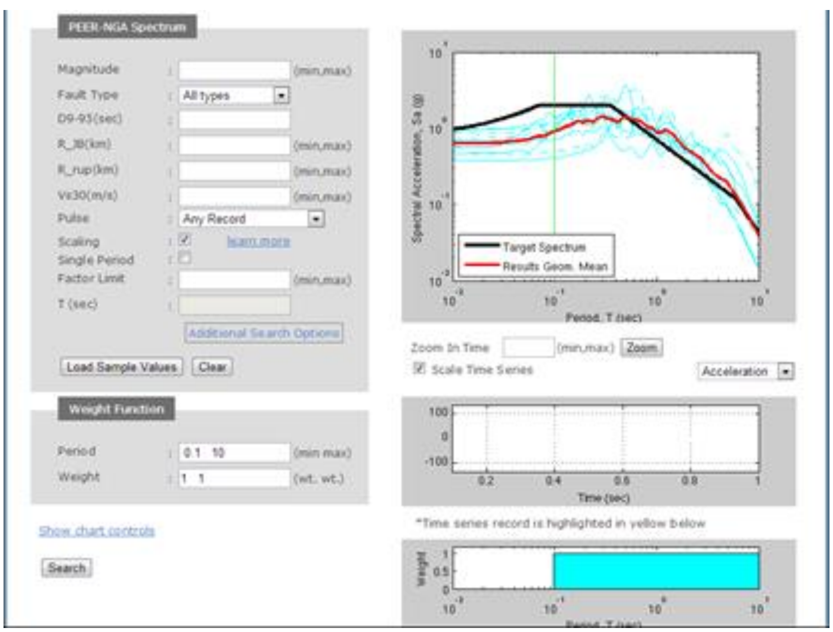


Fig. 2-13 Target specturm compared to other spectra generated by PMGD.

Step 3. Generating the scaled record using SeismoSoft

Once the scale factors are obtained from the PGMD, they are used in the SeismoSignal software to generate scaled earthquake records. The procedure for generating scaled earthquake records is as follows: The earthquake record to be scaled is selected, the appropriate time step is chosen and uploaded into the software. The scale factor is given as an input and then the record is scaled. The scaled record is then saved and is used in the analysis program (SAP2000) as an input for seismic analysis.

Selecting the earthquake record:

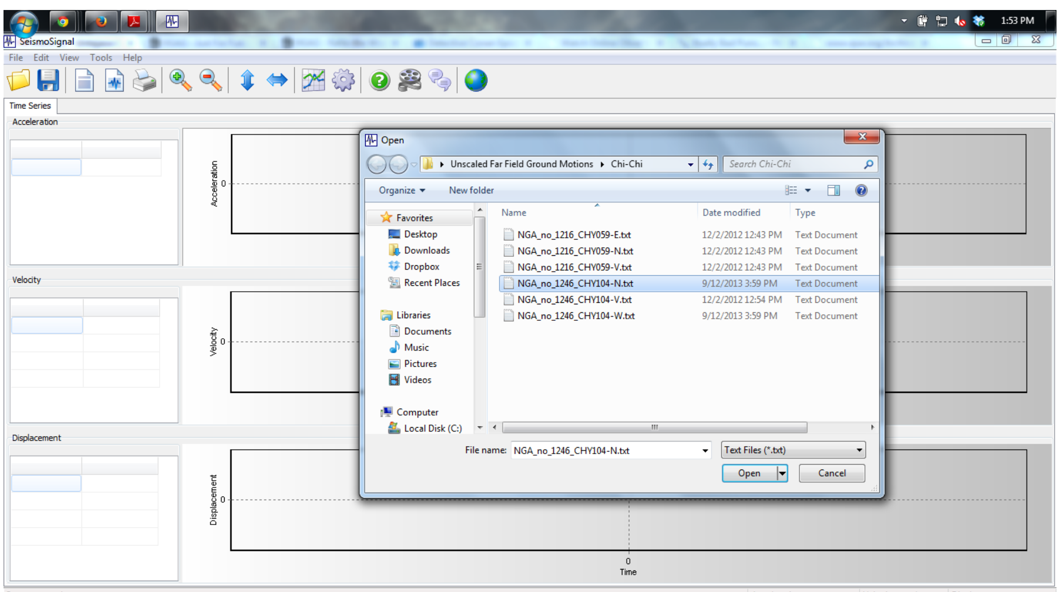


Fig. 2-14 Interface used to select earthquake records to be scaled.

Selecting the appropriate time step and other input file parameters:

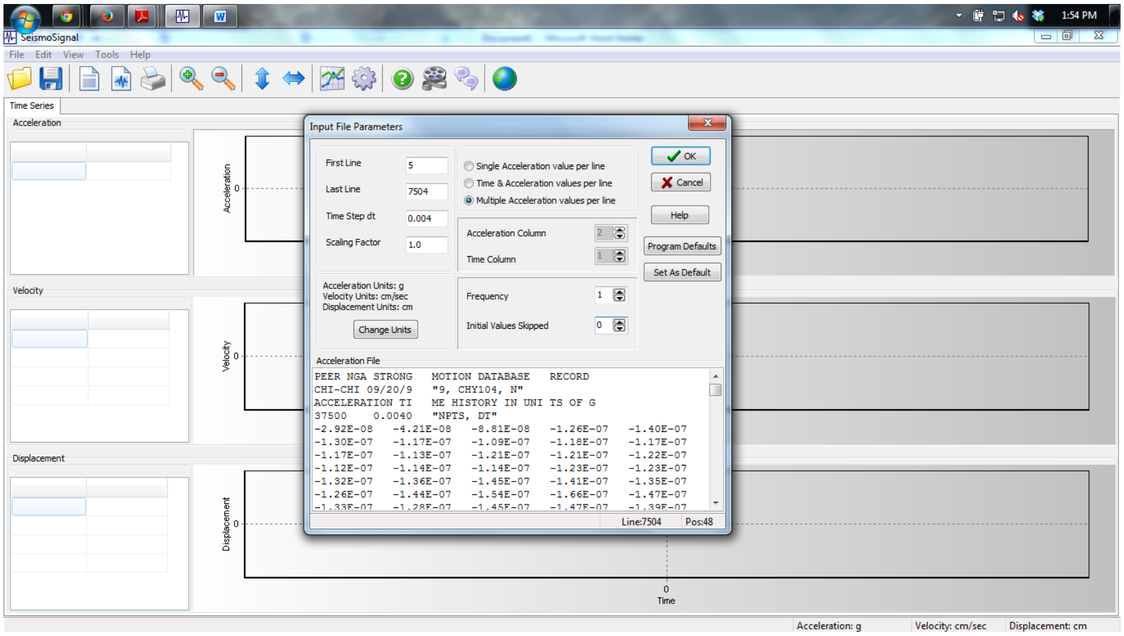


Fig. 2-15 Input file parameters.

Unscaled Time Series:

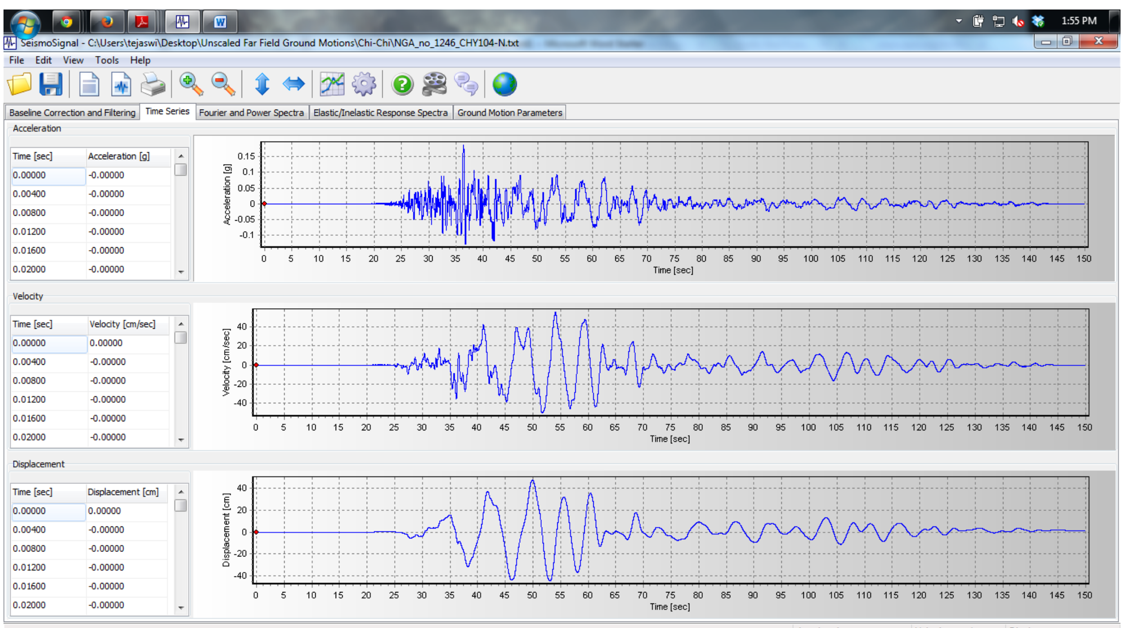


Fig. 2-16 Unscaled earthquake acclerograms.

Specifying the scale factor:

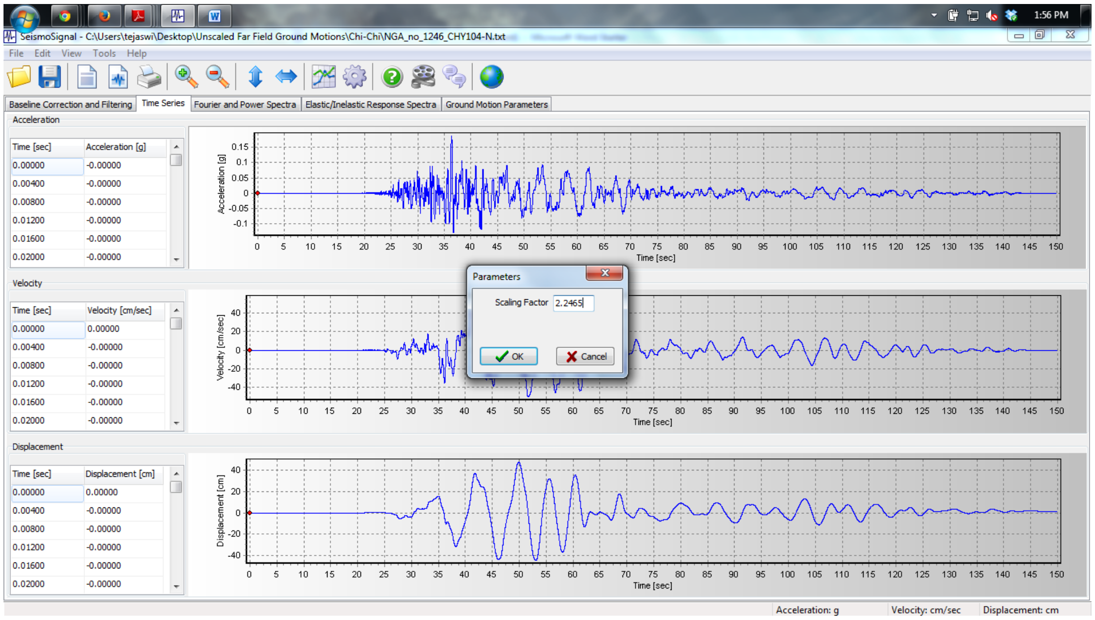


Fig. 2-17 Scale factor specification.

Scaled Time series:

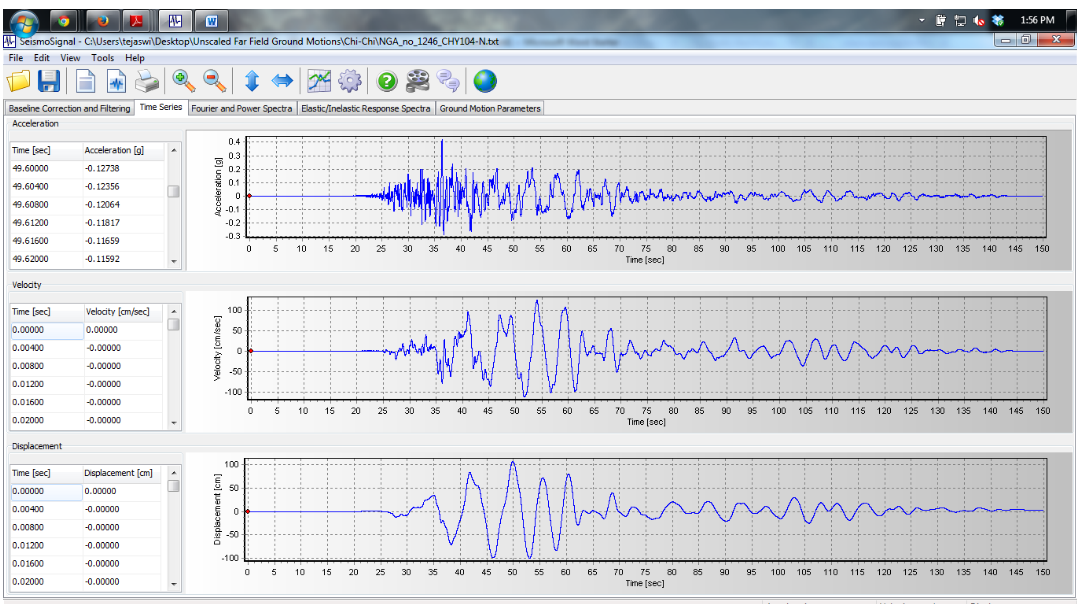


Fig. 2-18 Scaled earthquake acclerograms.

This procedure was followed for the 50 records evaluated in this study (28 NF and 22 FF). The scale factors for all the records are summarized in Table 2-7, and the time periods for both the isolated and control bridge cases are summarized in Table 2-8 and Table 2-9.

Table 2-7 Scale factors for Very High, High, and Medium to High intensities

Record Sequence Number	Earthquake Name	Very High	High	Medium to High
125	Friuli, Italy-01	4.3232	1.6742	0.9643
161	Imperial Valley-06	3.5166	1.3619	0.7844
169	Imperial Valley-06	2.2672	0.878	0.5057
170	Imperial Valley-06	2.5698	0.9952	0.5372
179	Imperial Valley-06	1.8381	0.7118	0.41
180	Imperial Valley-06	1.4522	0.5624	0.3239
183	Imperial Valley-06	1.775	0.6874	0.3959
752	Loma Prieta	2.5911	1.0034	0.578
802	Loma Prieta	2.0866	0.8081	0.4654
827	Cape Mendocino	4.6365	1.7955	1.0342
864	Landers	2.9421	1.1394	0.6563
879	Landers	1.6693	0.6465	0.3724
960	Northridge-01	2.2595	0.875	0.504
1044	Northridge-01	1.4285	0.5532	0.3186
1050	Northridge-01	4.2052	1.6285	0.938
1051	Northridge-01	1.5947	0.6176	0.3557
1086	Northridge-01	1.438	0.5569	0.3208
1116	Kobe, Japan	3.6243	1.4035	0.8084
1158	Kocaeli, Turkey	1.7889	0.6928	0.399
1246	Chi-Chi, Taiwan	2.2465	0.8706	0.5011
1489	Chi-Chi, Taiwan	2.2259	0.862	0.4965
1493	Chi-Chi, Taiwan	2.9279	1.1339	0.6531
1494	Chi-Chi, Taiwan	2.6758	1.0362	0.5969
1602	Duzce, Turkey	1.6048	0.6215	0.358
1787	Hector Mine	2.7857	1.0788	0.6214

Table 2-8 Time periods for isolated bridges

Bridge	Kiso (K/ft.)	Col. Ht.(ft)	Time Period(X)	Time Period(Y)
2 Span	90	25	6.256509	0.2216
	270	25	3.640868	0.22106
	180	25	4.441609	0.22133
2 Span L.C	90	50	6.422243	0.33869
	270	50	3.920354	0.32085
	180	50	4.672846	0.32936
3 Span L.C 360'	90	50	5.561949	0.43937
	270	50	3.39578	0.43694
	180	50	4.047172	0.43799
3 Span L.C 400'	90	50	5.862738	0.51009
	270	50	3.579158	0.50627
	180	50	4.265911	0.50798
3 Span 400'	90	25	5.711342	0.50981
	270	25	3.323572	0.50425
	180	25	4.054556	0.50698
3 Span 360'	90	25	5.398308	0.43908
	270	25	3.118598	0.43493
	180	25	3.818334	0.43697
4 Span 480'	90	25	5.108377	0.74533
	270	25	2.972698	0.72557
	180	25	3.626503	0.73517
4 Span 560'	90	25	5.517666	0.97863
	270	25	3.210852	0.94354
	180	25	3.917053	0.96032
4 Span L.C 480'	90	50	5.243924	0.74603
	270	50	3.201896	0.73062
	180	50	3.815897	0.73766
4 Span L.C 560'	90	50	5.66397	0.97947
	270	50	3.457958	0.95145
	180	50	4.121351	0.96425

Table 2-9 Time periods for bridges without any isolators

Bridge	Col. Ht.(ft)	Time Period(X)	Time Period(Y)
2 Span	25	0.56414	0.19807
2 Span L.C	50	1.58497	0.22822
3 Span L.C 360'	50	1.38749	0.42958
3 Span L.C 400'	50	1.45786	0.49052
3 Span 400'	25	0.51597	0.33409
3 Span 360'	25	0.49045	0.30089
4 Span 480'	25	0.46329	0.35756
4 Span 560'	25	0.4985	0.41248
4 Span L.C 480'	50	1.31328	0.6532
4 Span L.C 560'	50	1.41017	0.80597

CHAPTER THREE - RESULTS AND DISCUSSIONS OF ISOLATOR RESPONSE TO NEAR FIELD EARTHQUAKE GROUND MOTIONS

The results shown in this chapter include plots of response quantities for various parameters when subjected to near field earthquake ground motions. Table 3-1 shows the list of the near field ground motions used. The table shows the NGA record sequence numbers and the earthquake names. The parameters include the isolator stiffness, high intensity scaled earthquakes(H), medium to high intensity scaled earthquakes(MH), and very high intensity scaled earthquakes(VH). The response quantities include the following: Longitudinal Displacement (Ux), Transverse Displacement (Uy), Longitudinal Base Shear (Vx), Transverse Base Shear (Vy), and period of vibration. The vertical axis represents the base shear or the displacement values. The horizontal axis represents the NGA record sequence number. The units used for displacement values is feet, the units used for base shear is kips, and the units used for stiffness values is kips per feet. The nodes which had the maximum values of longitudinal and transverse displacements were used to generate the displacement curves. The Control case represents the case where no isolators are provided.

Table 3-1 List of Near Field ground motions.

No.	NGA record sequence number
1	1044-FN
2	1044-FP
3	1050-FN
4	1050-FP
5	1051-FN
6	1051-FP
7	1086-FN
8	1086-FP
9	1489-FN
10	1489-FP
11	1493-FN
12	1493-FP
13	1494-FN
14	1494-FP
15	161-FN
16	161-FP
17	170-FN
18	170-FP
19	179-FN
20	179-FP
21	180-FN
22	180-FP
23	183-FN
24	183-FP
25	802-FN
26	802-FP
27	879-FN
28	879-FP

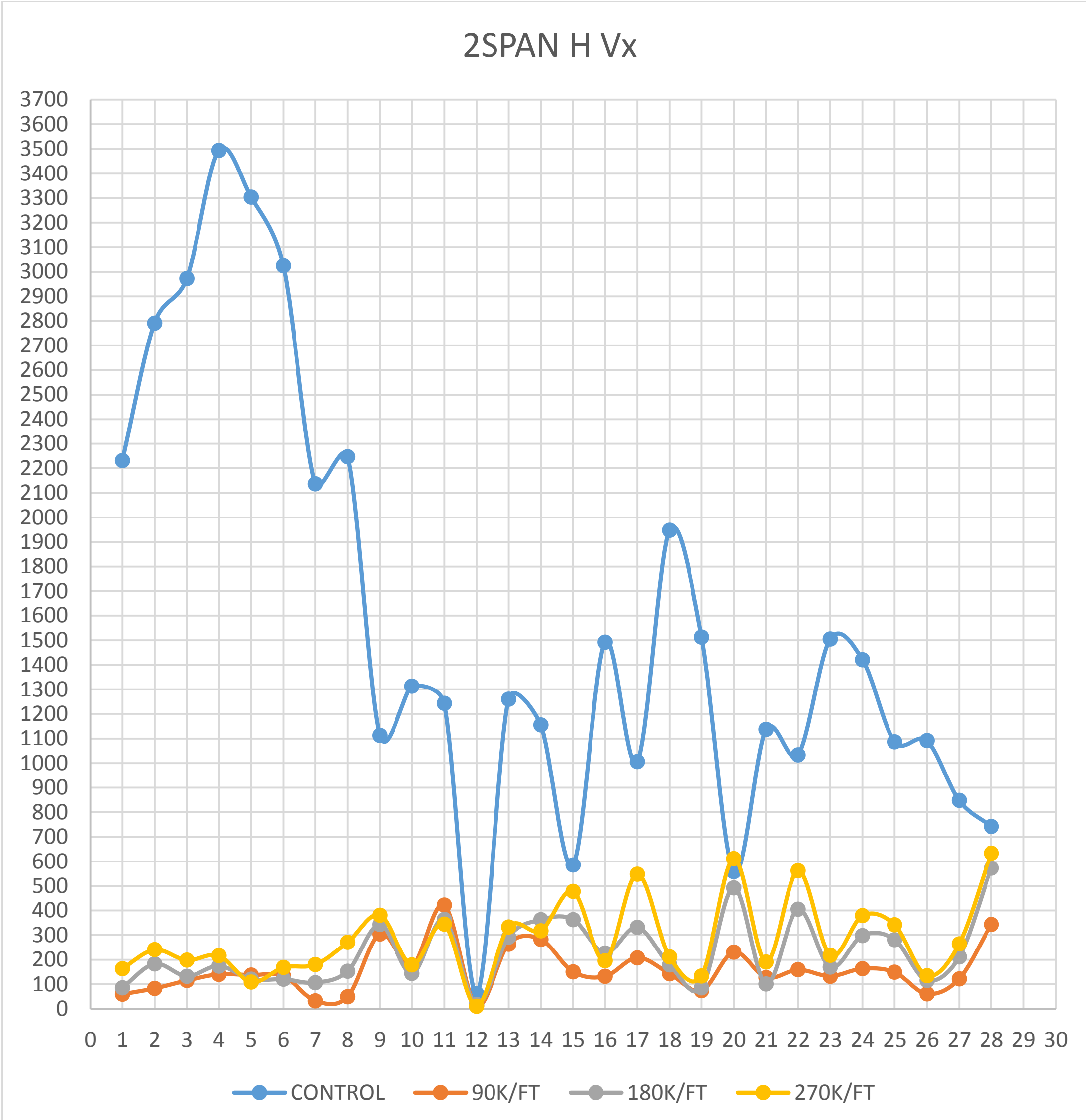


Fig. 3-1 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

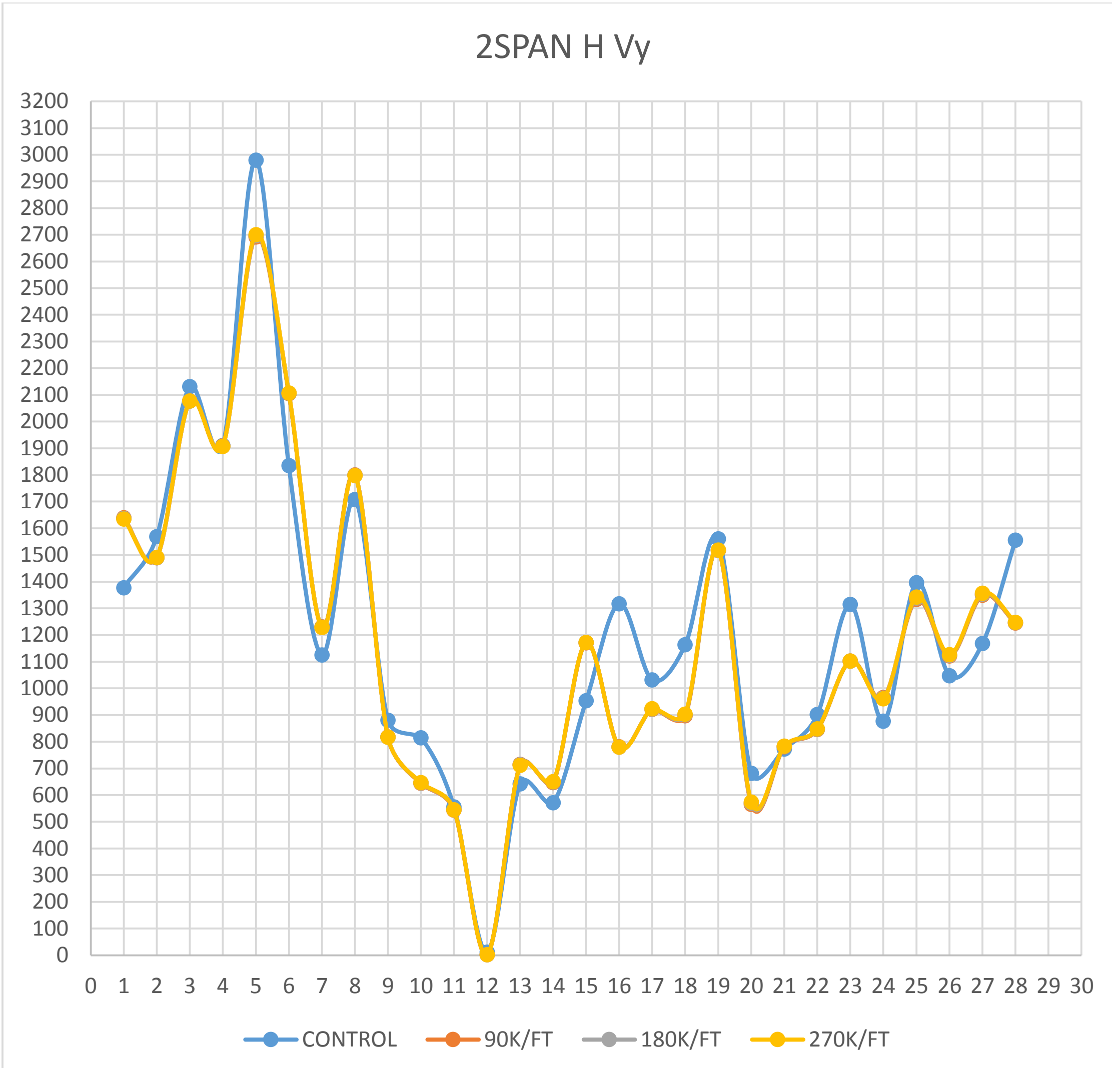


Fig. 3-2 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

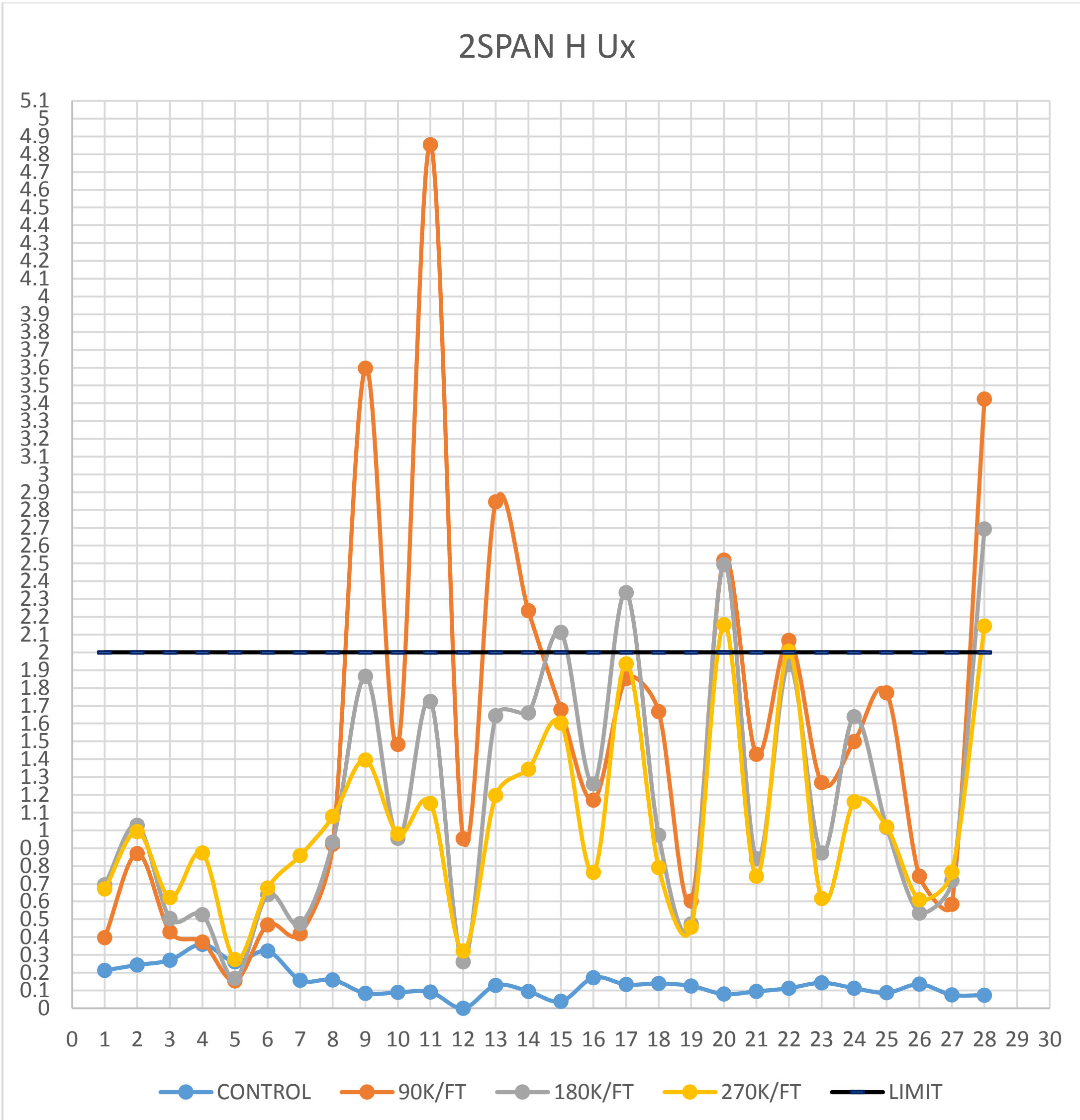


Fig. 3-3 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

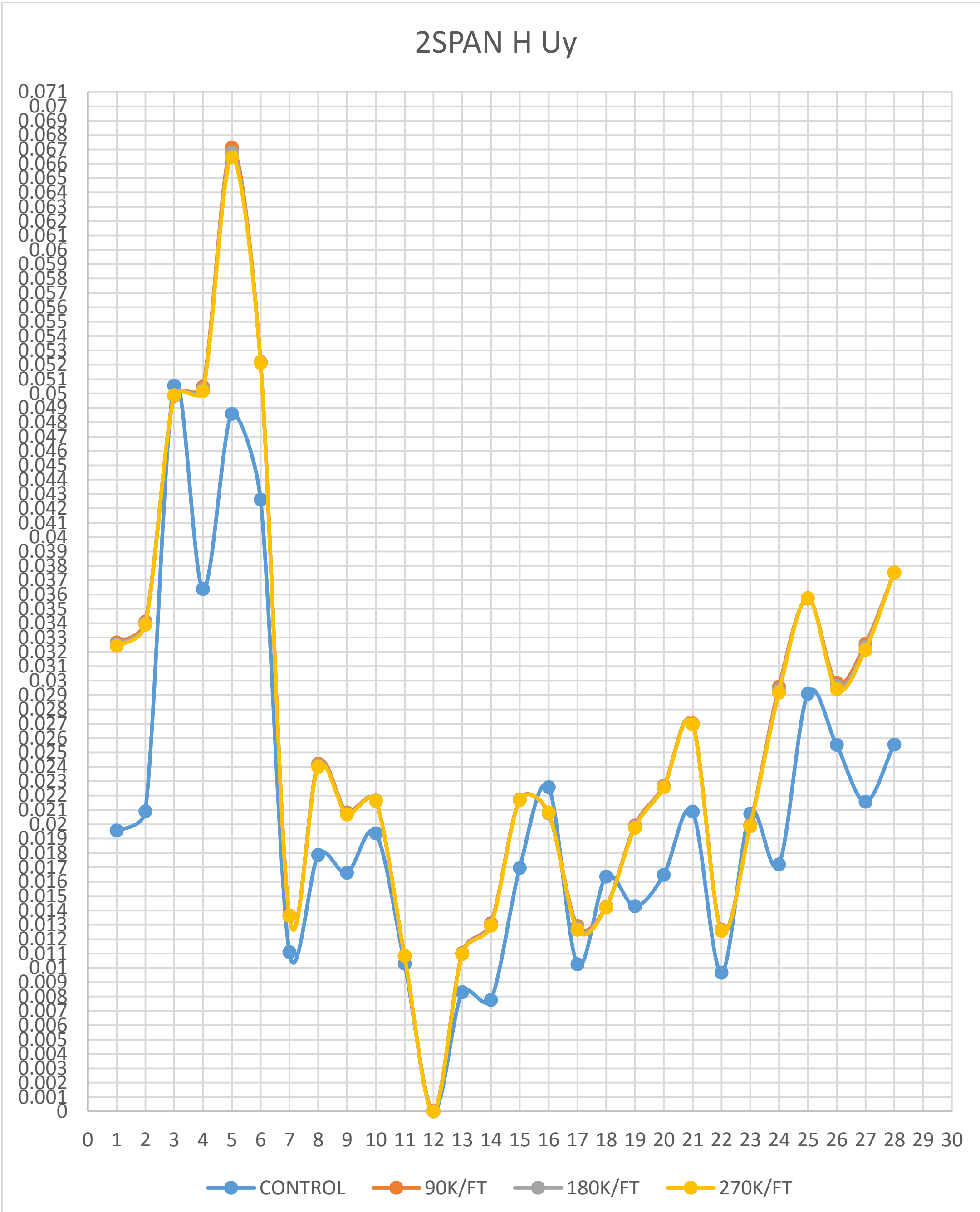


Fig. 3-4 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

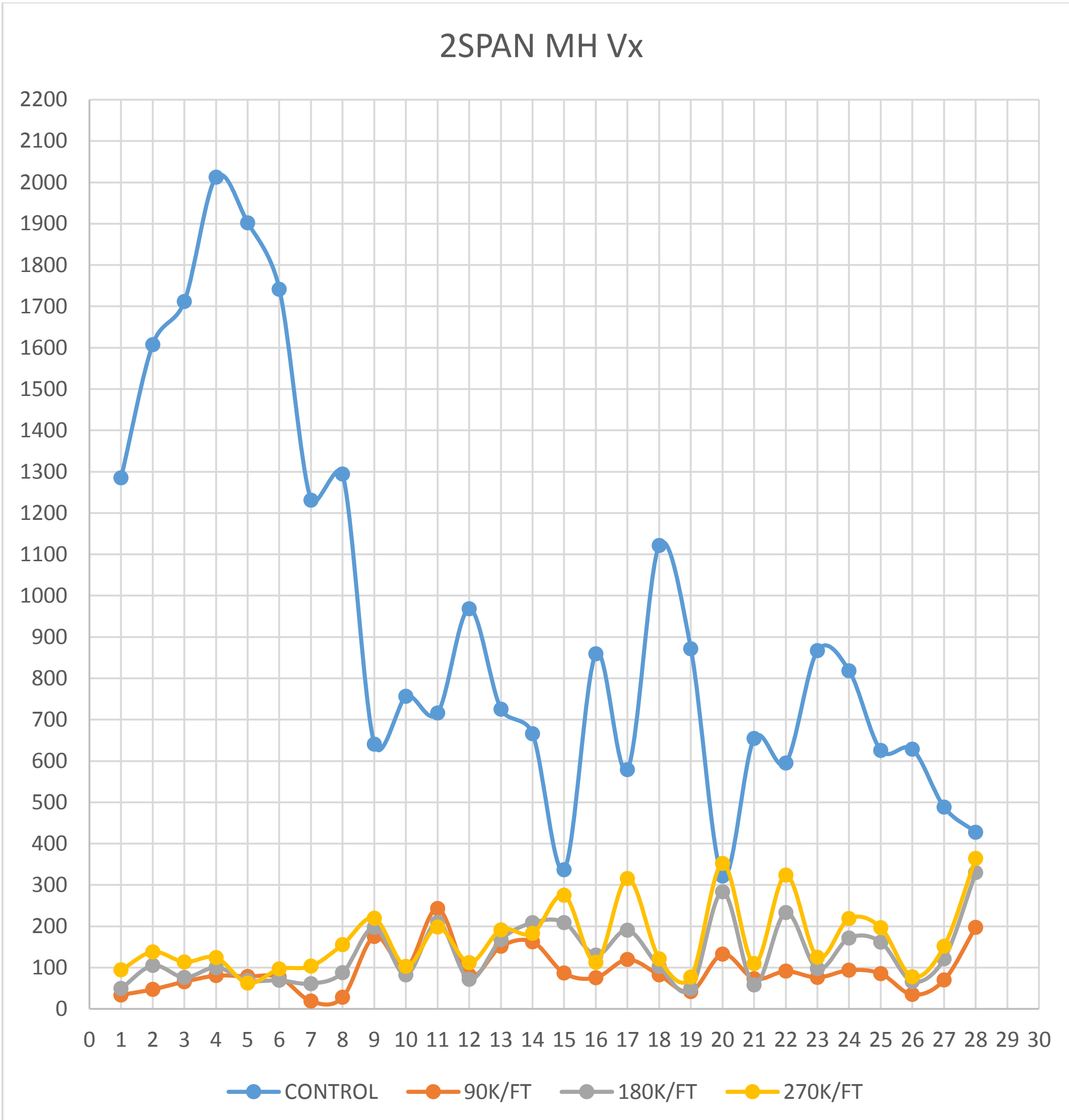


Fig. 3-5 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

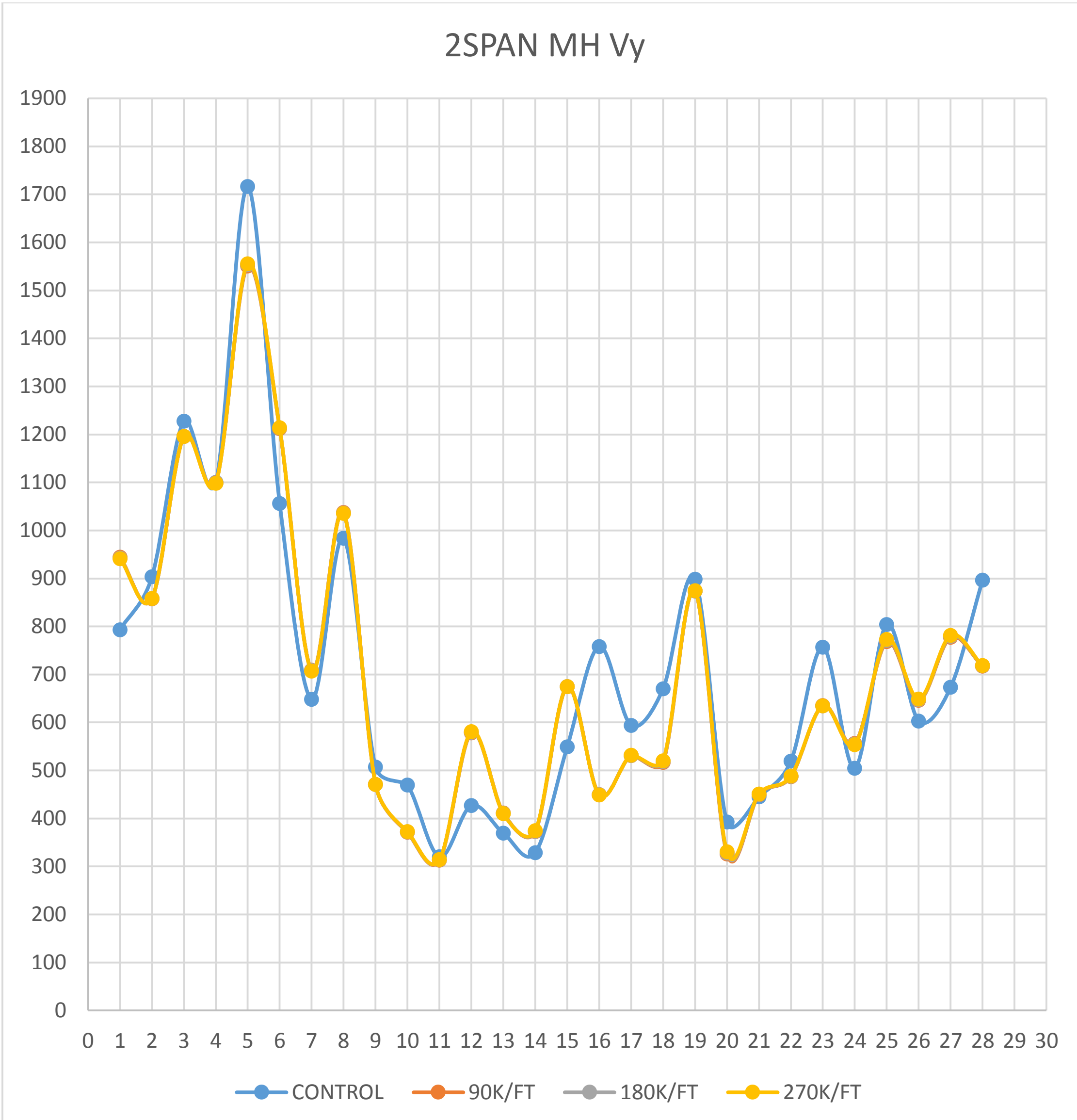


Fig. 3-6 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

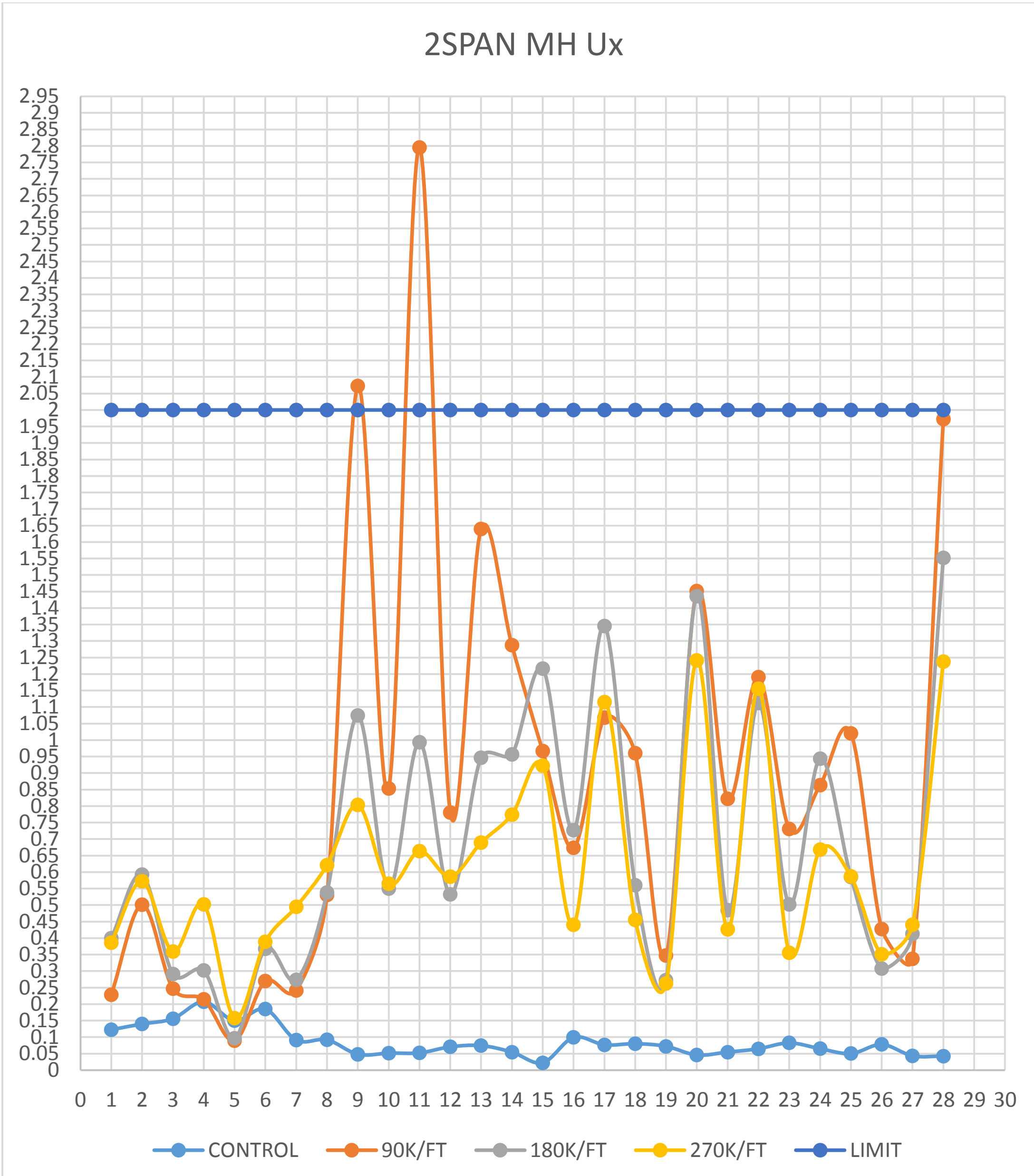


Fig. 3-7 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

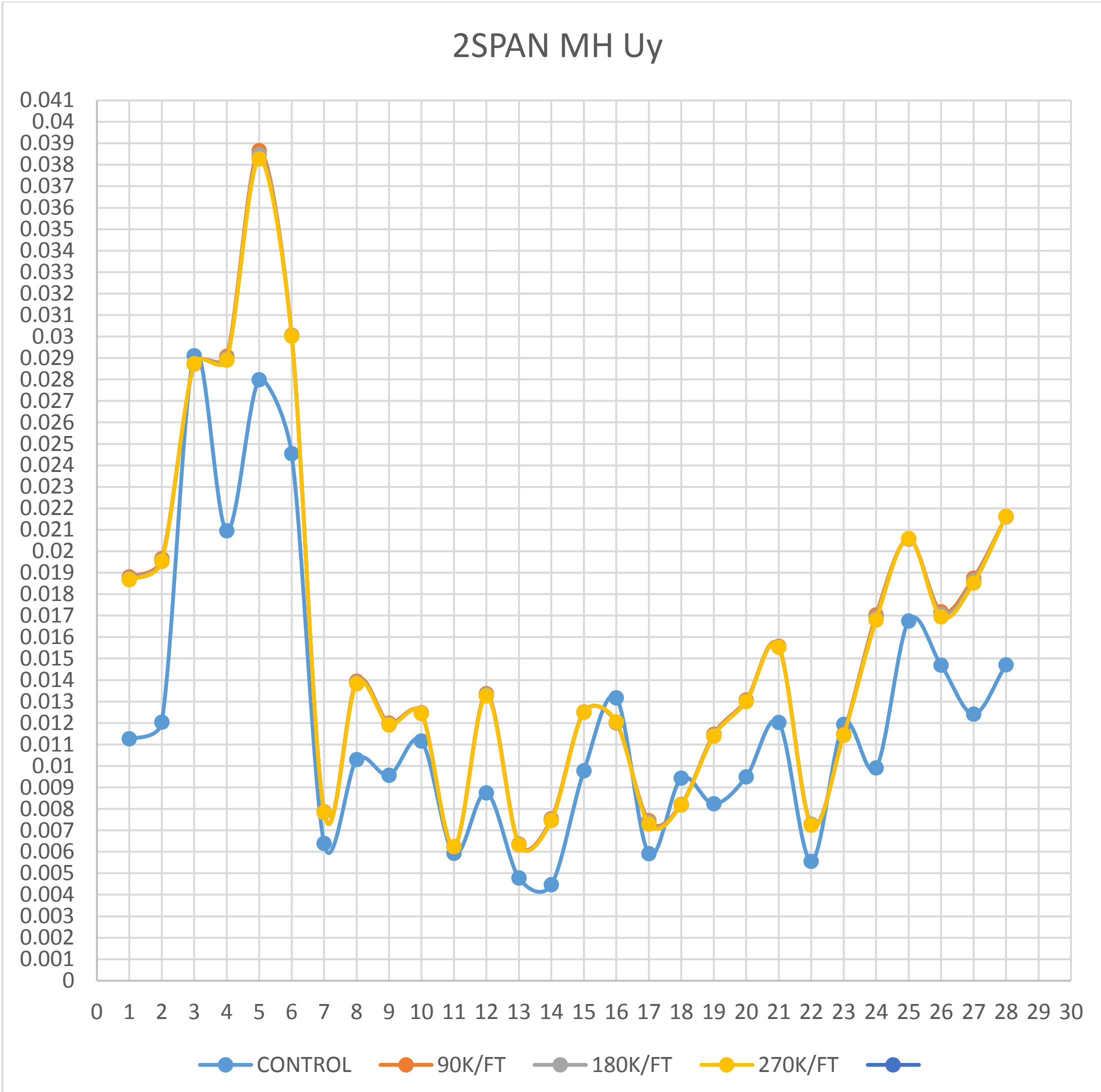


Fig. 3-8 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

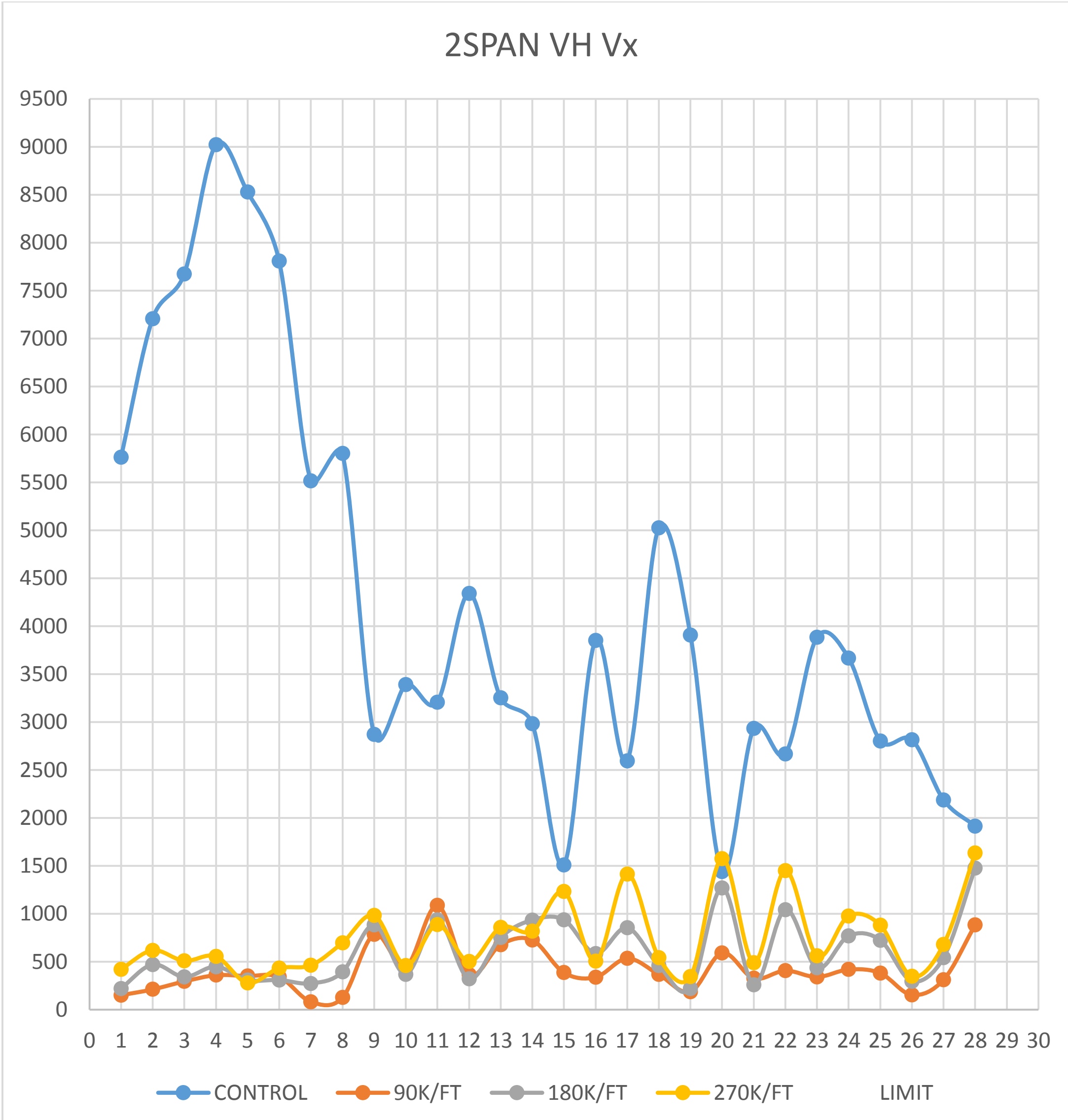


Fig. 3-9 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

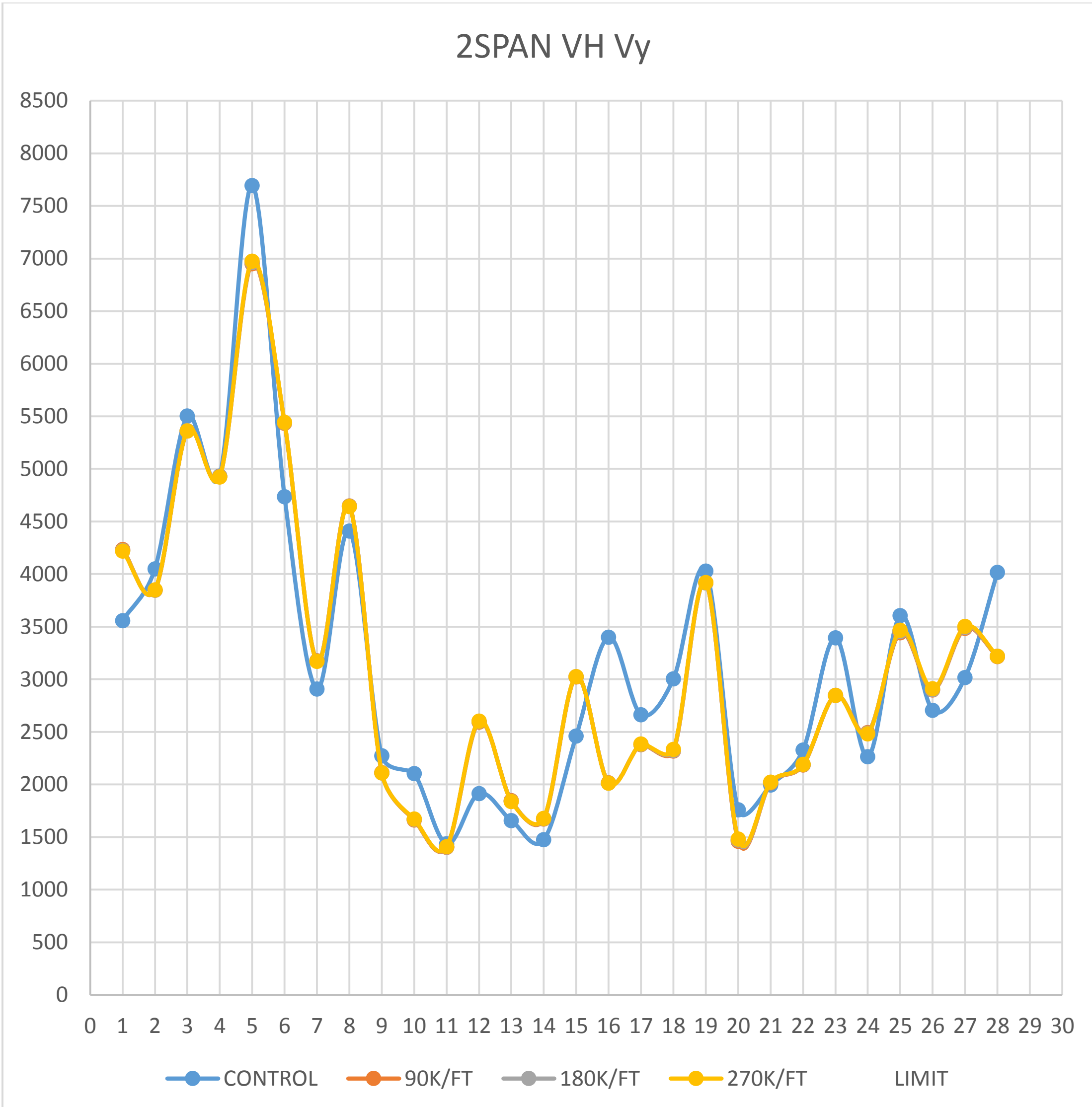


Fig. 3-10 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

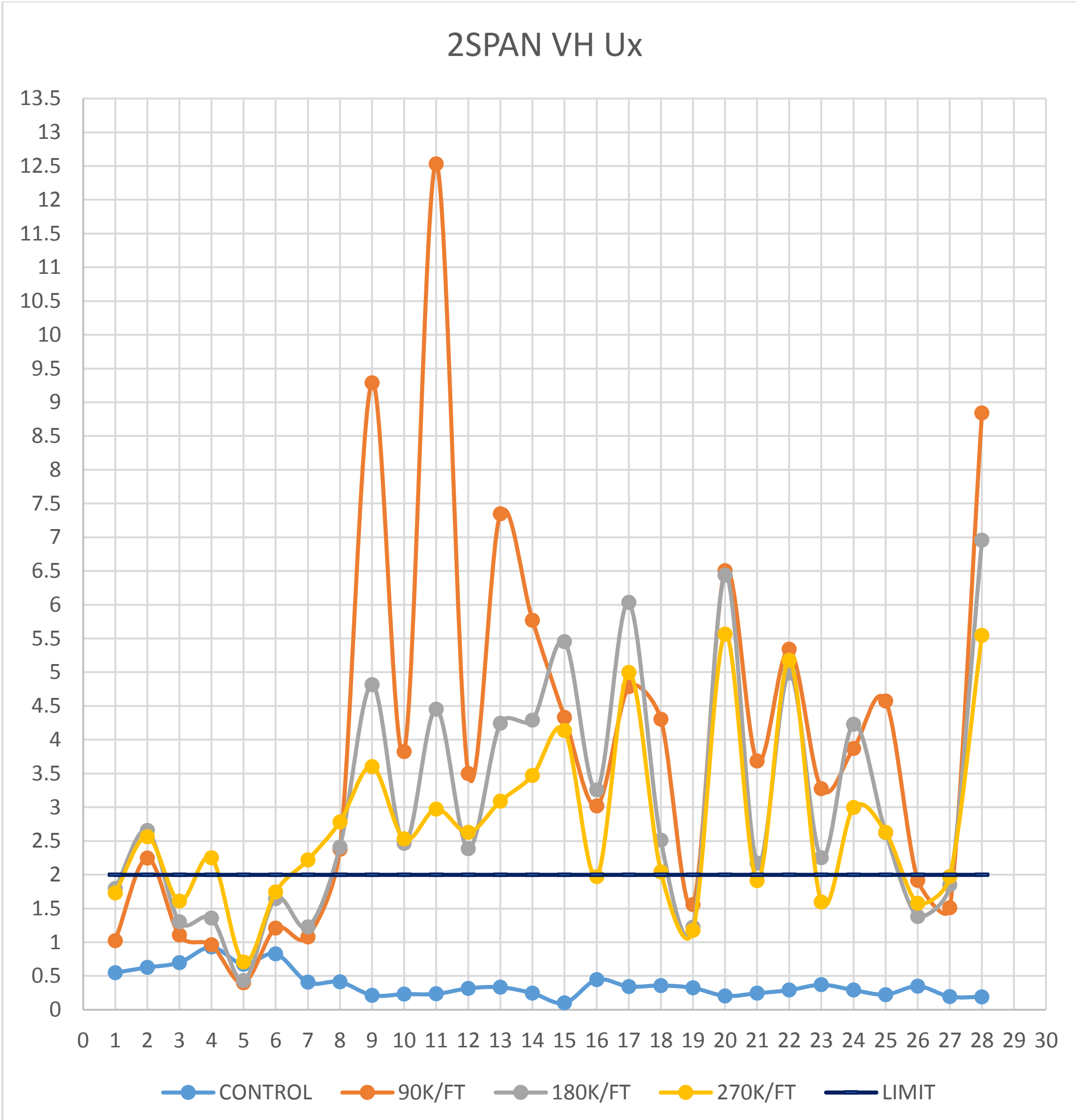


Fig. 3-11 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

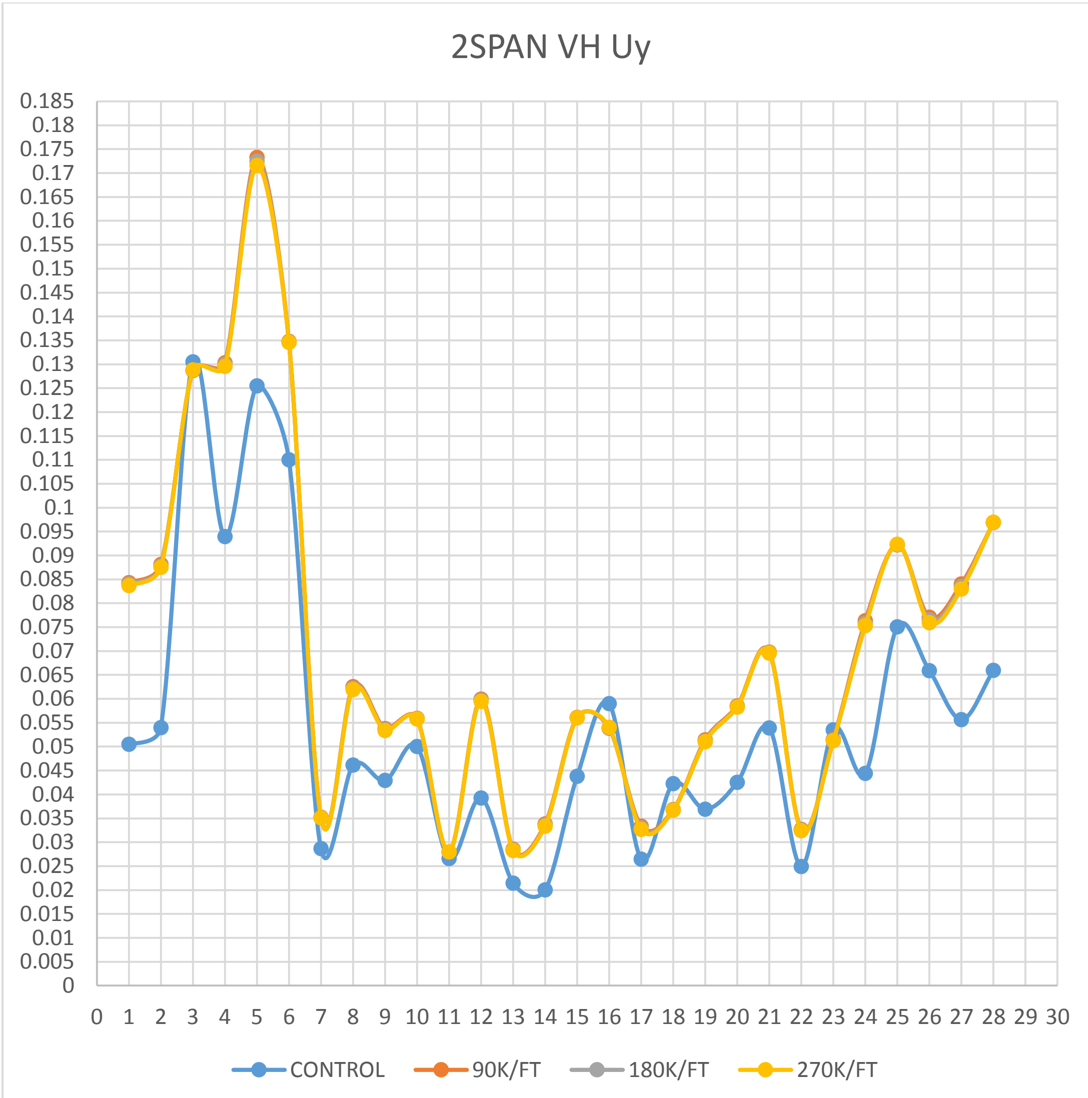


Fig. 3-12 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 2 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for quite a few cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 2 span bridge show us that 90, 180 and 270 kips per feet can be used as isolation stiffness without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 2 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 9021.844

90 K/Ft = 1088.983

180 K/Ft = 1478.463

270 K/Ft = 1634.116

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

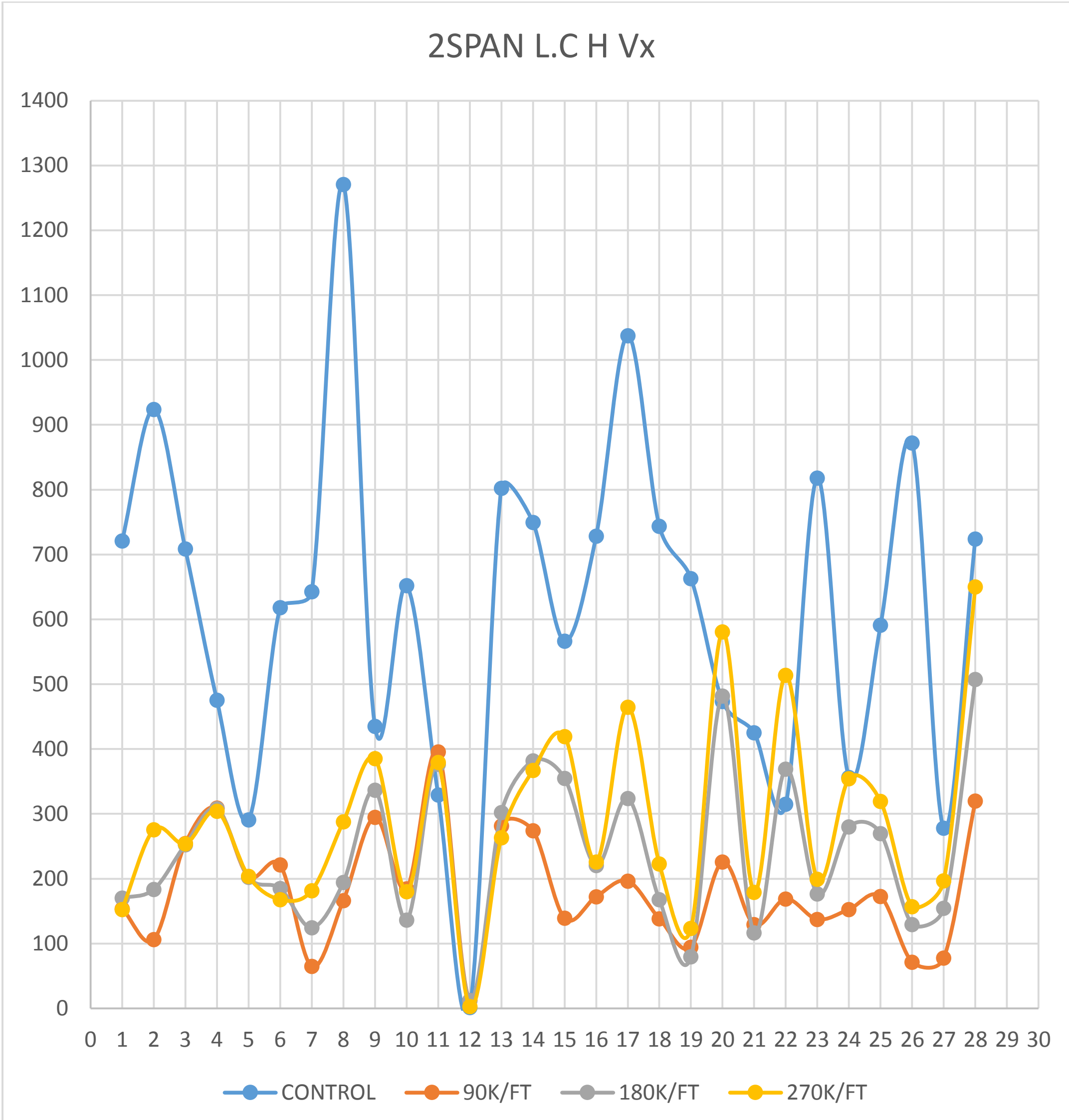


Fig. 3-13 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

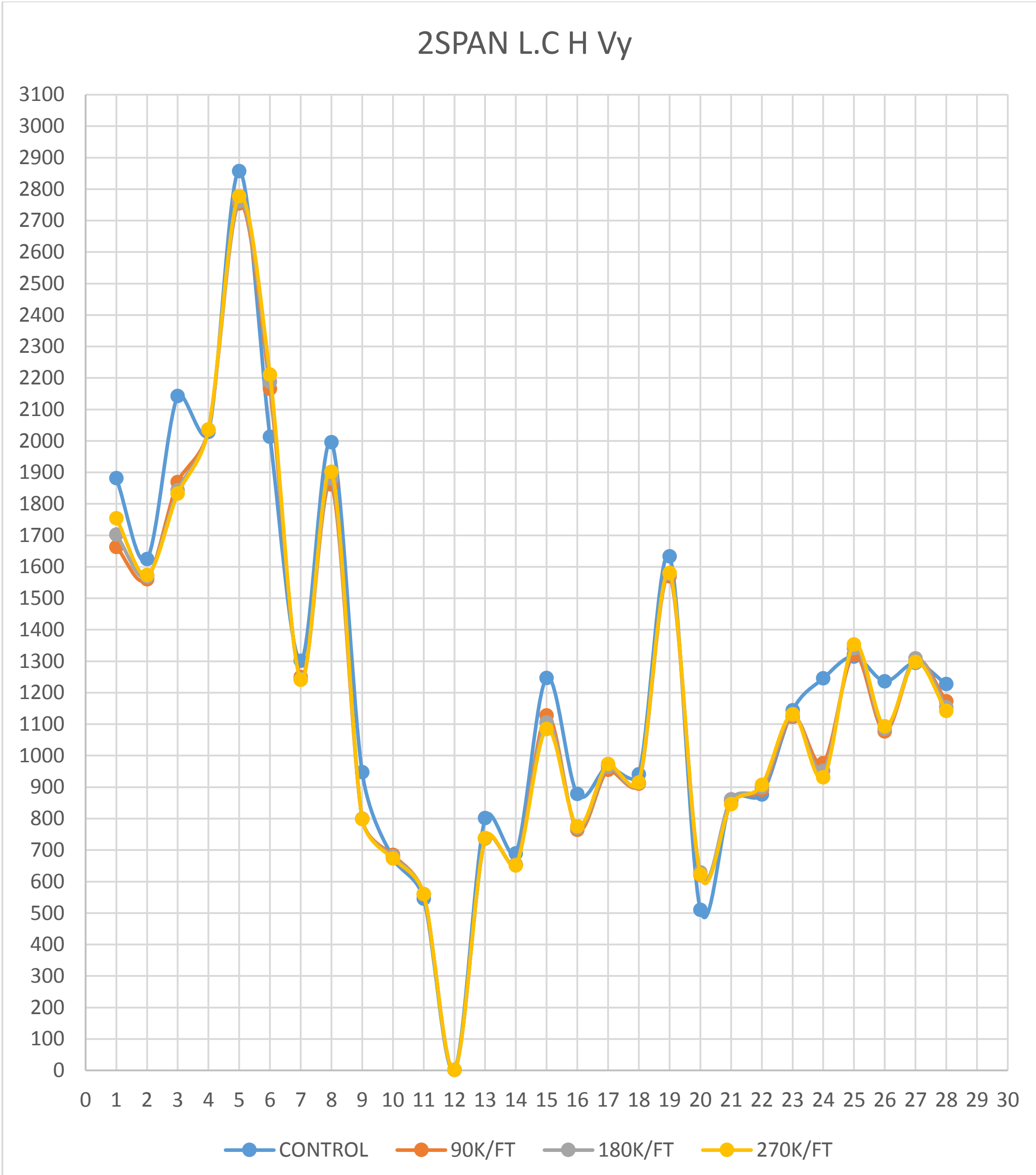


Fig. 3-14 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

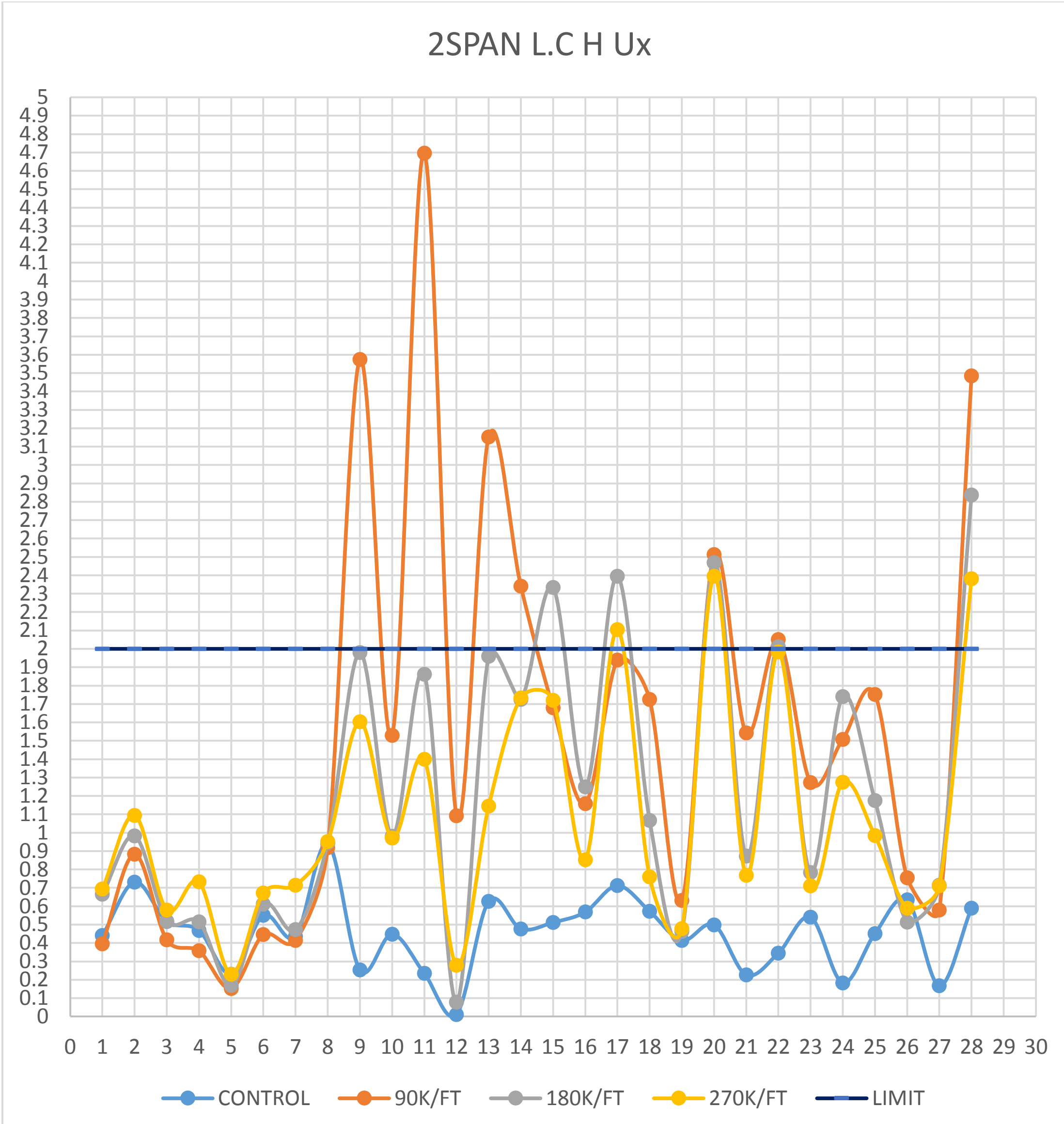


Fig. 3-15 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

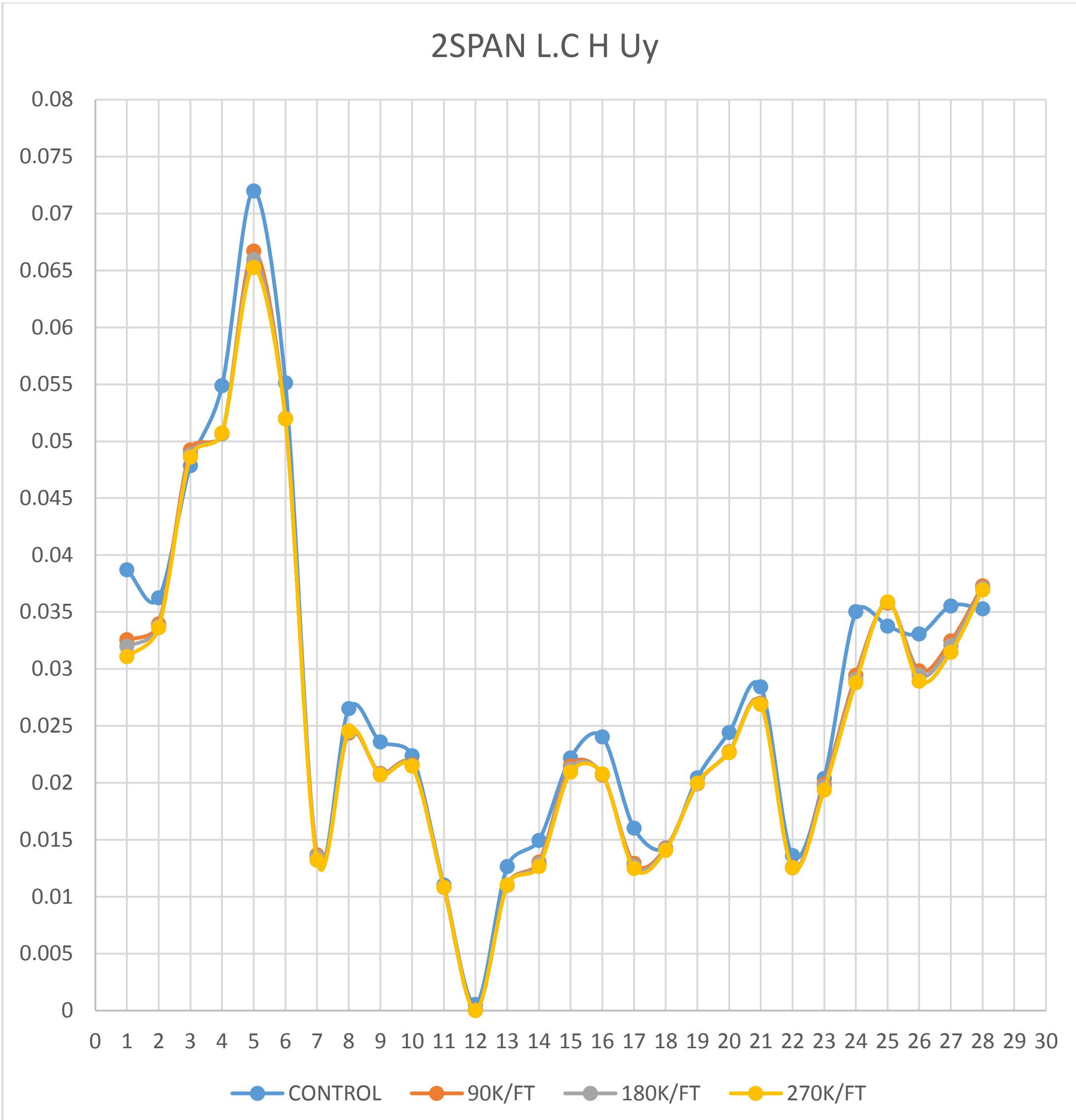


Fig. 3-16 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the two span bridge.

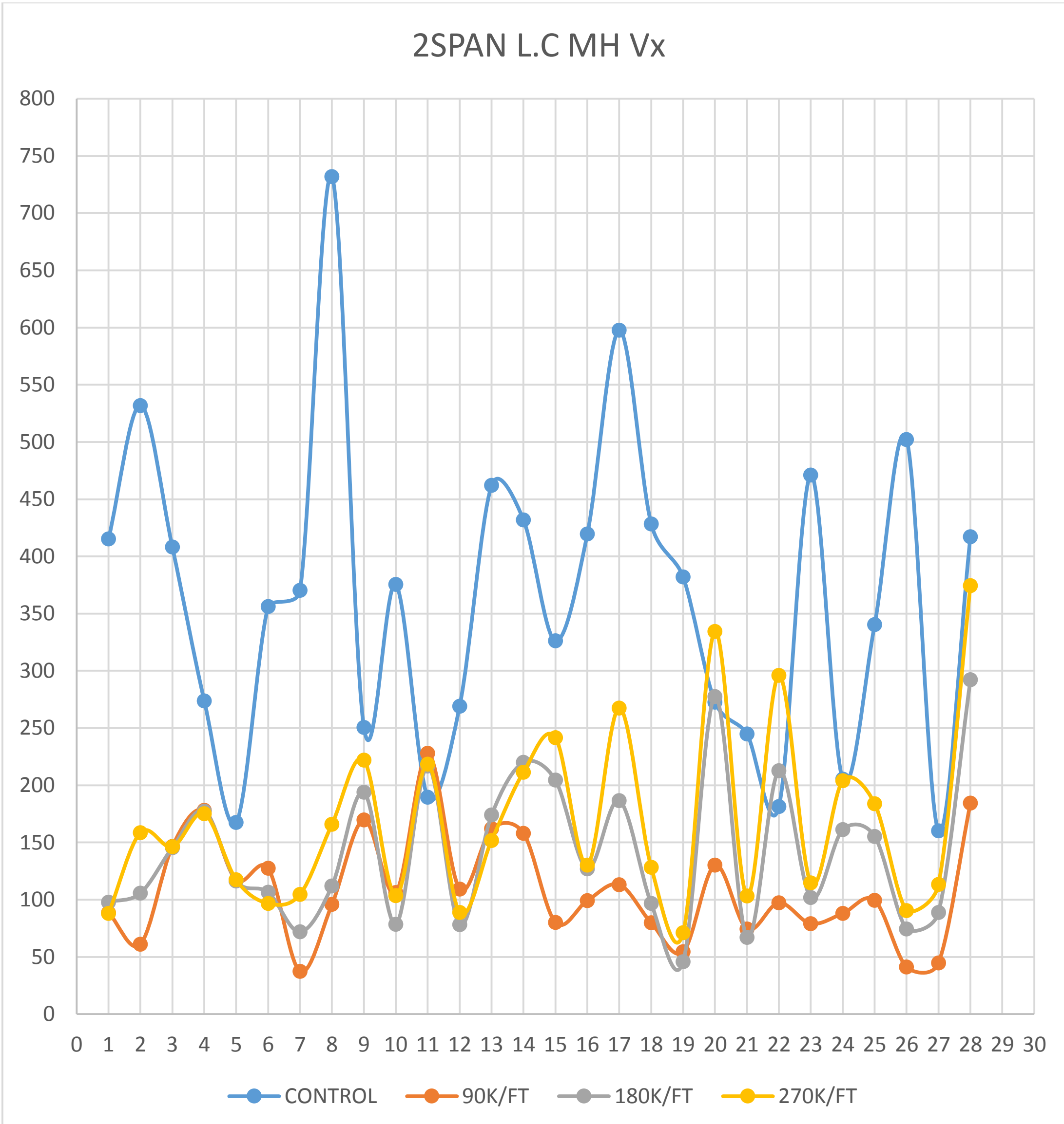


Fig. 3-17 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

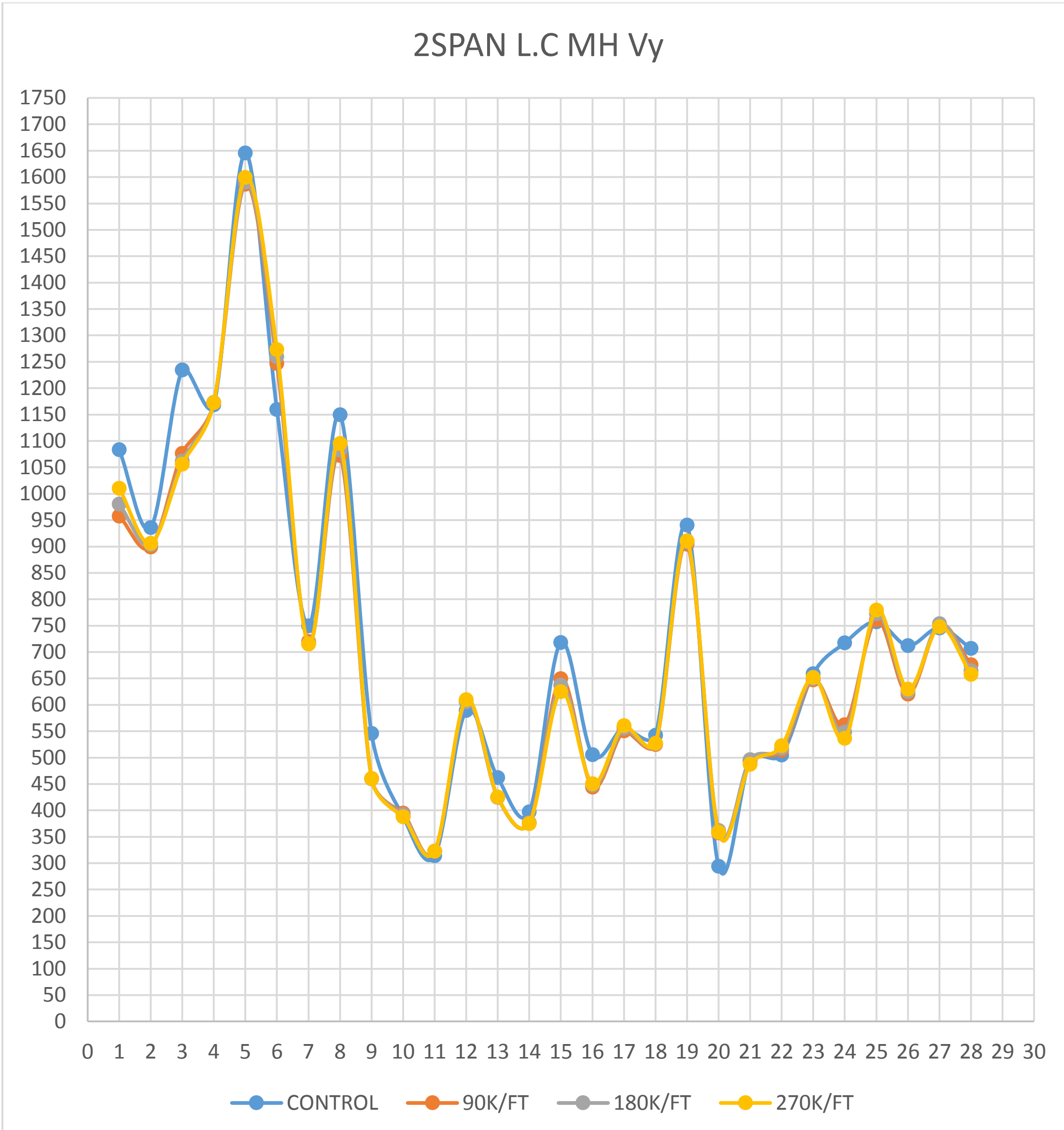


Fig. 3-18 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

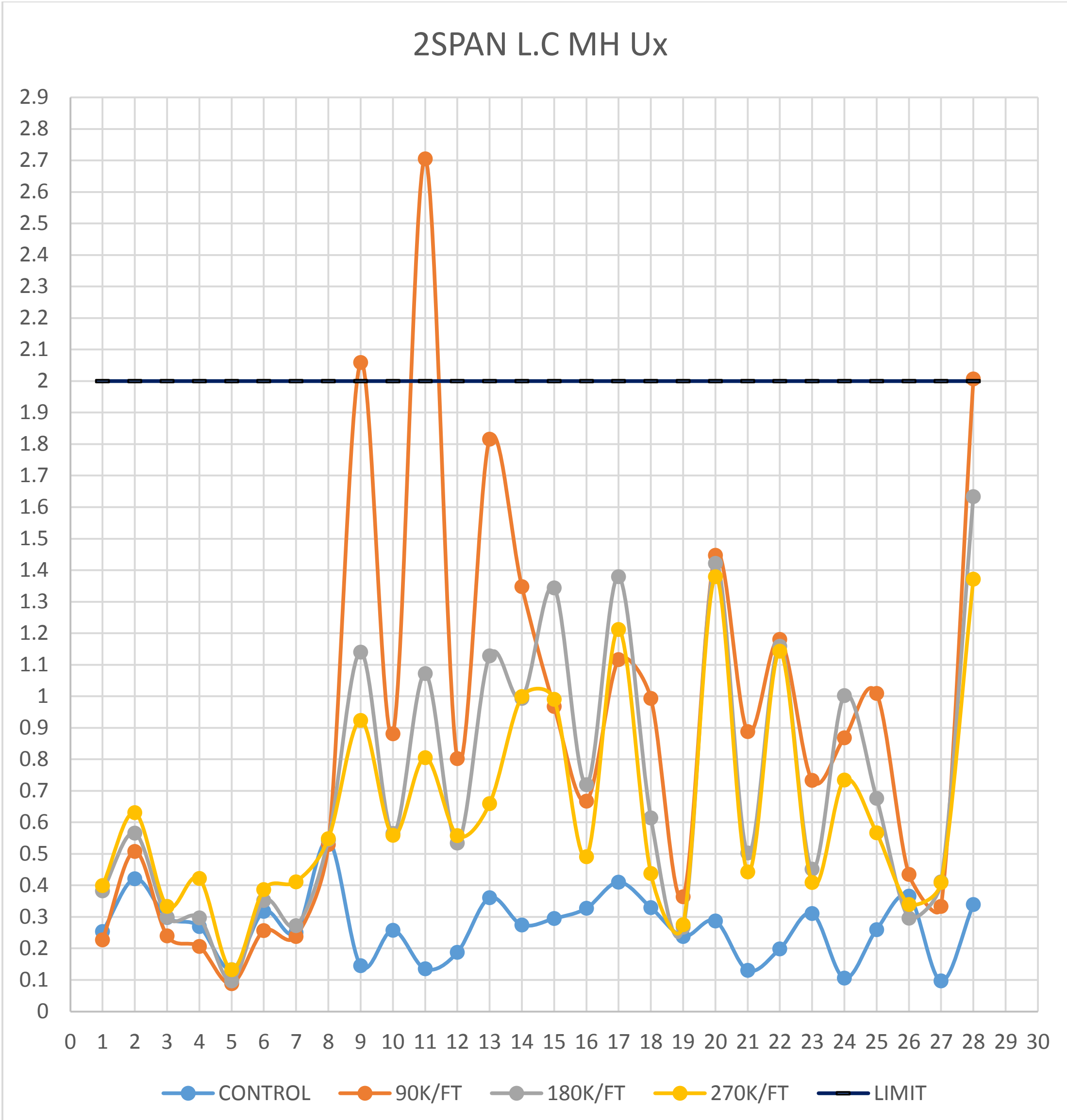


Fig. 3-19 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

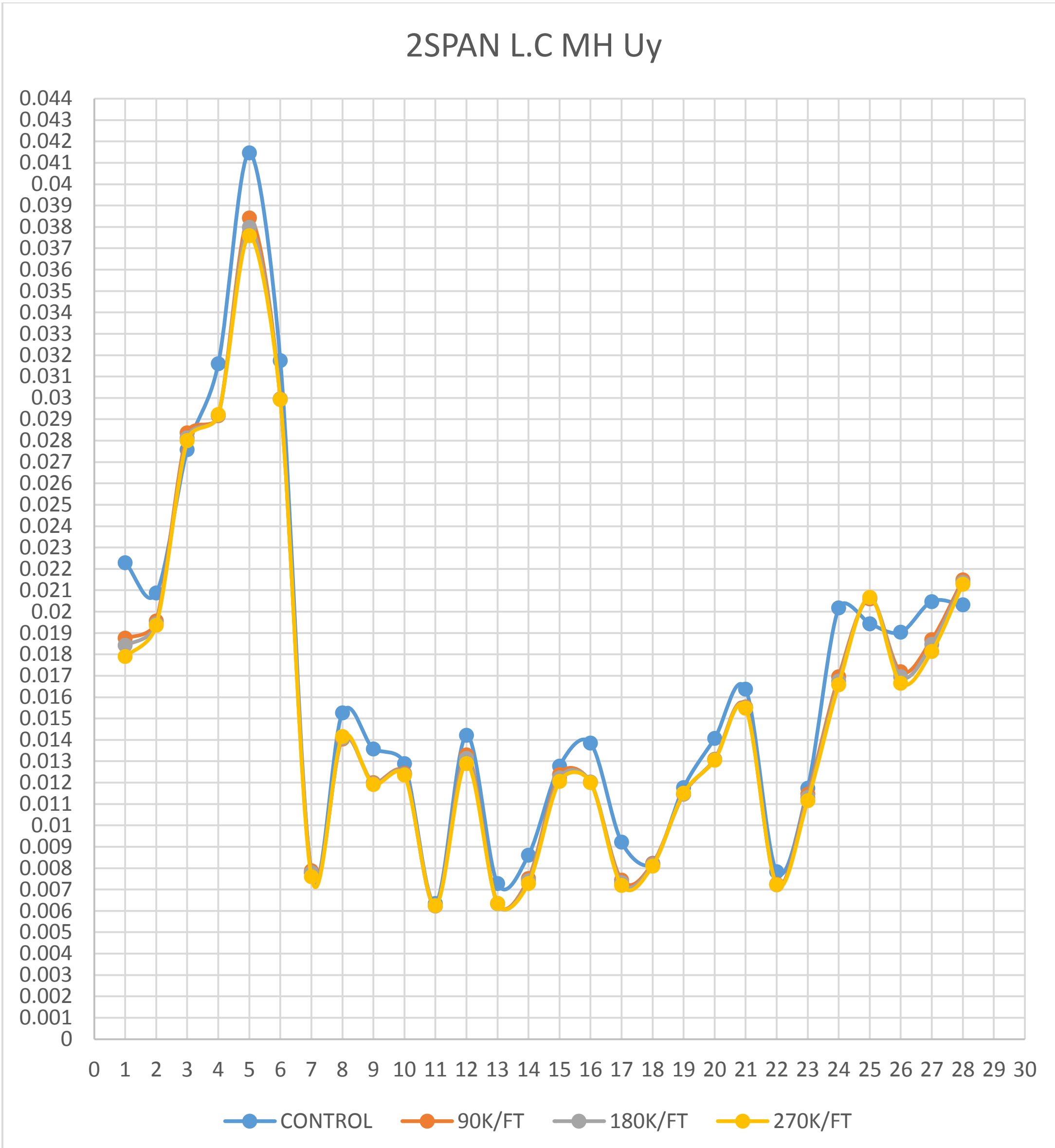


Fig. 3-20 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the two span bridge.

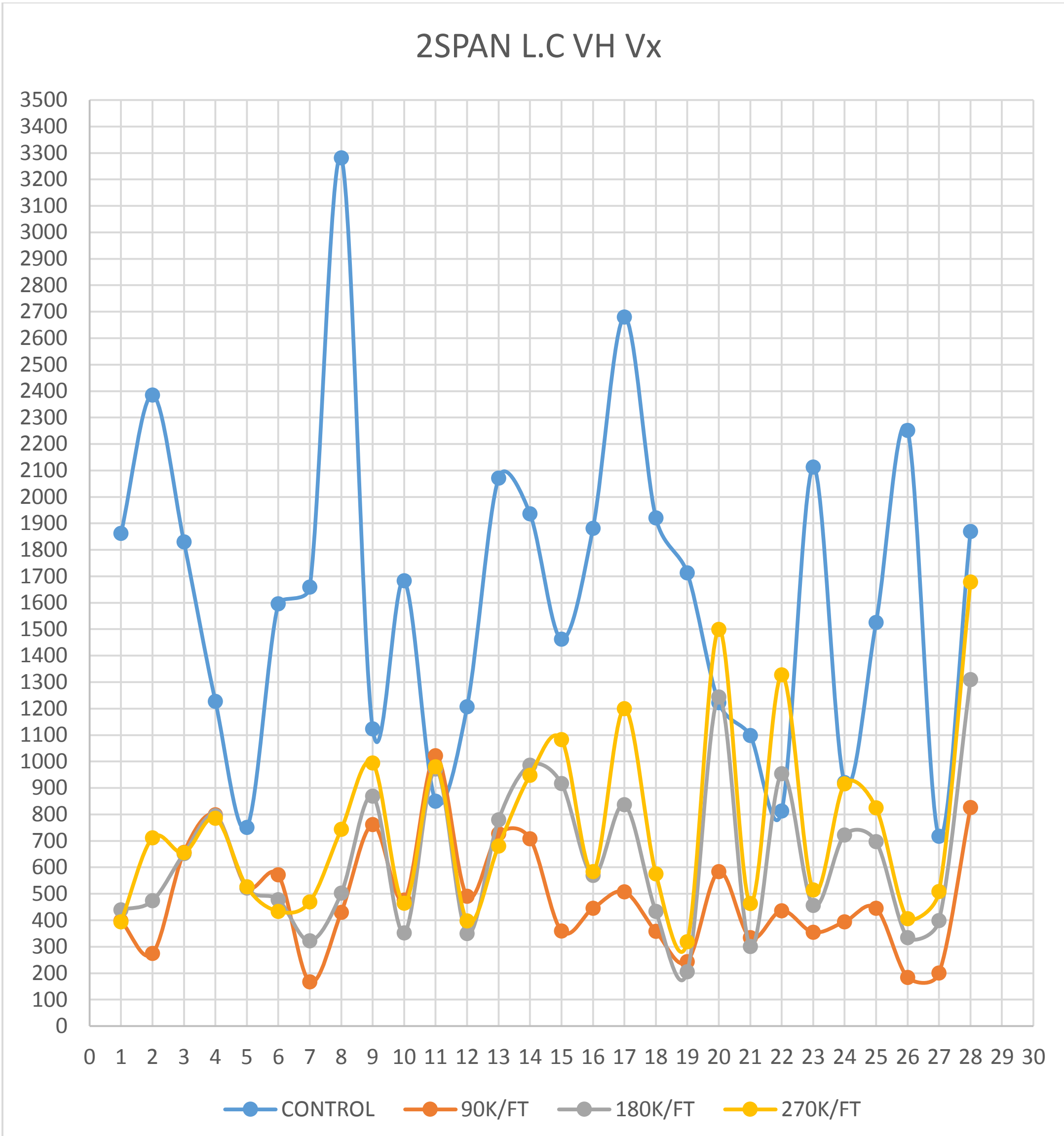


Fig. 3-21 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

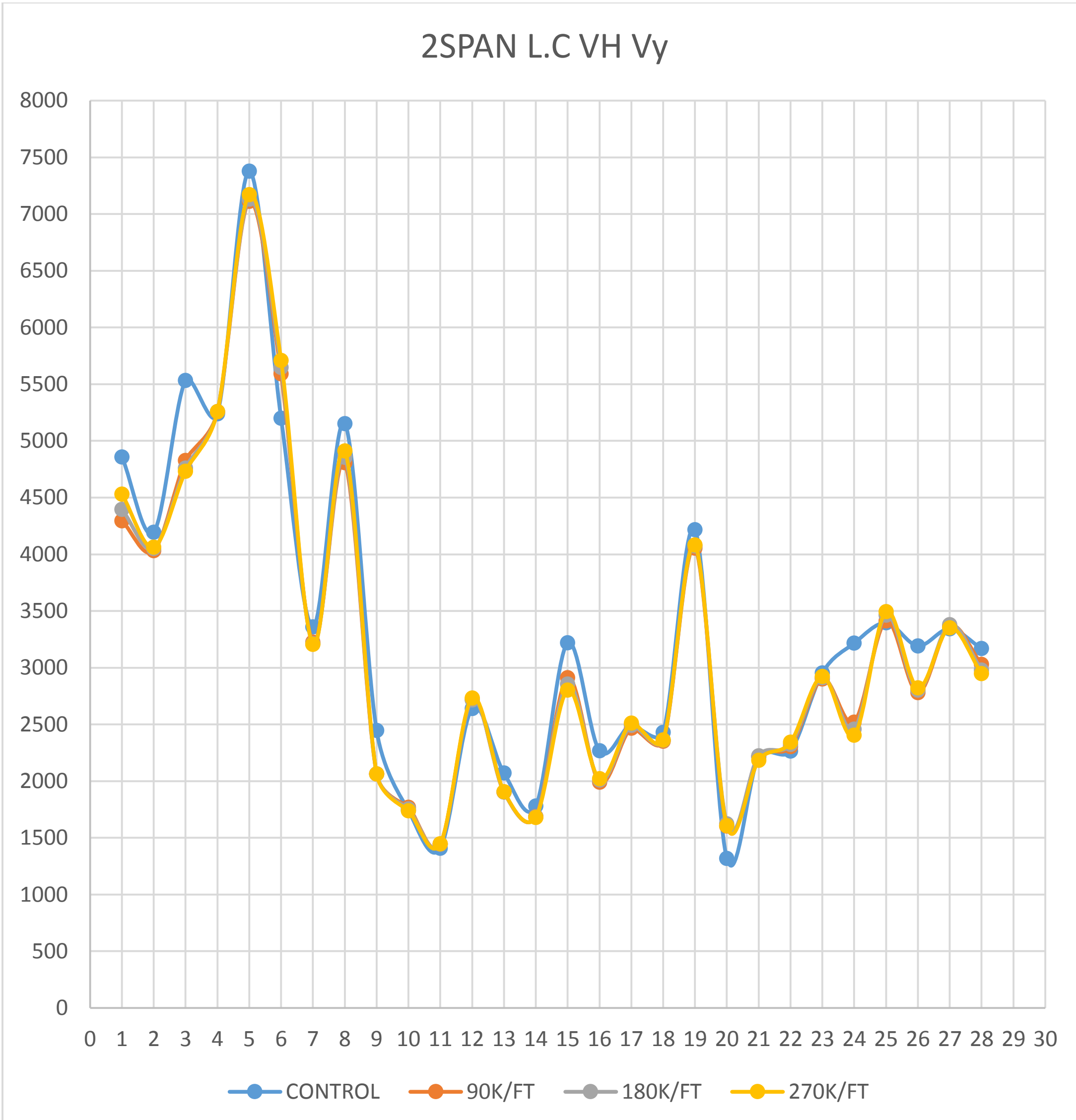


Fig. 3-22 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

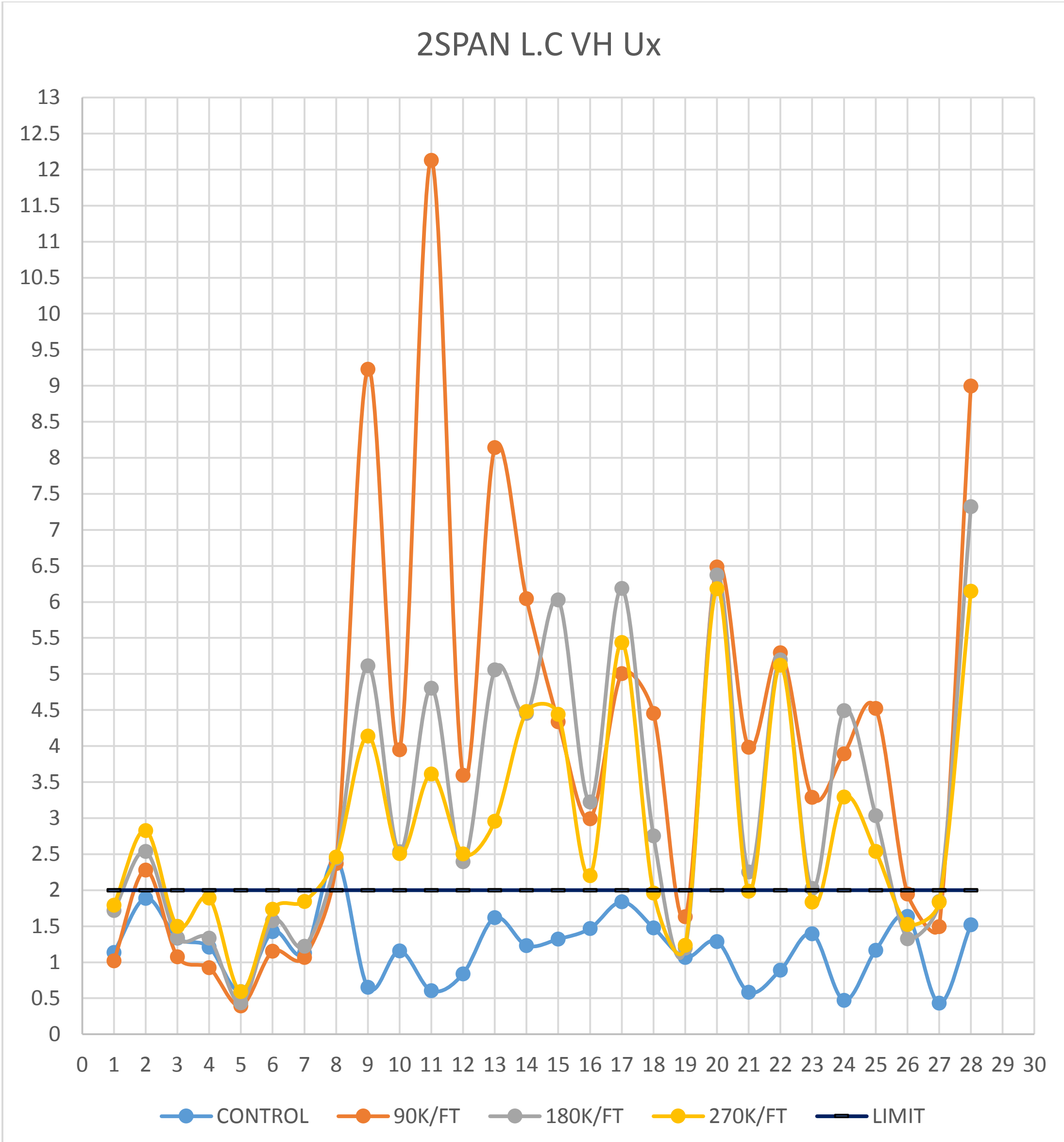


Fig. 3-23 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

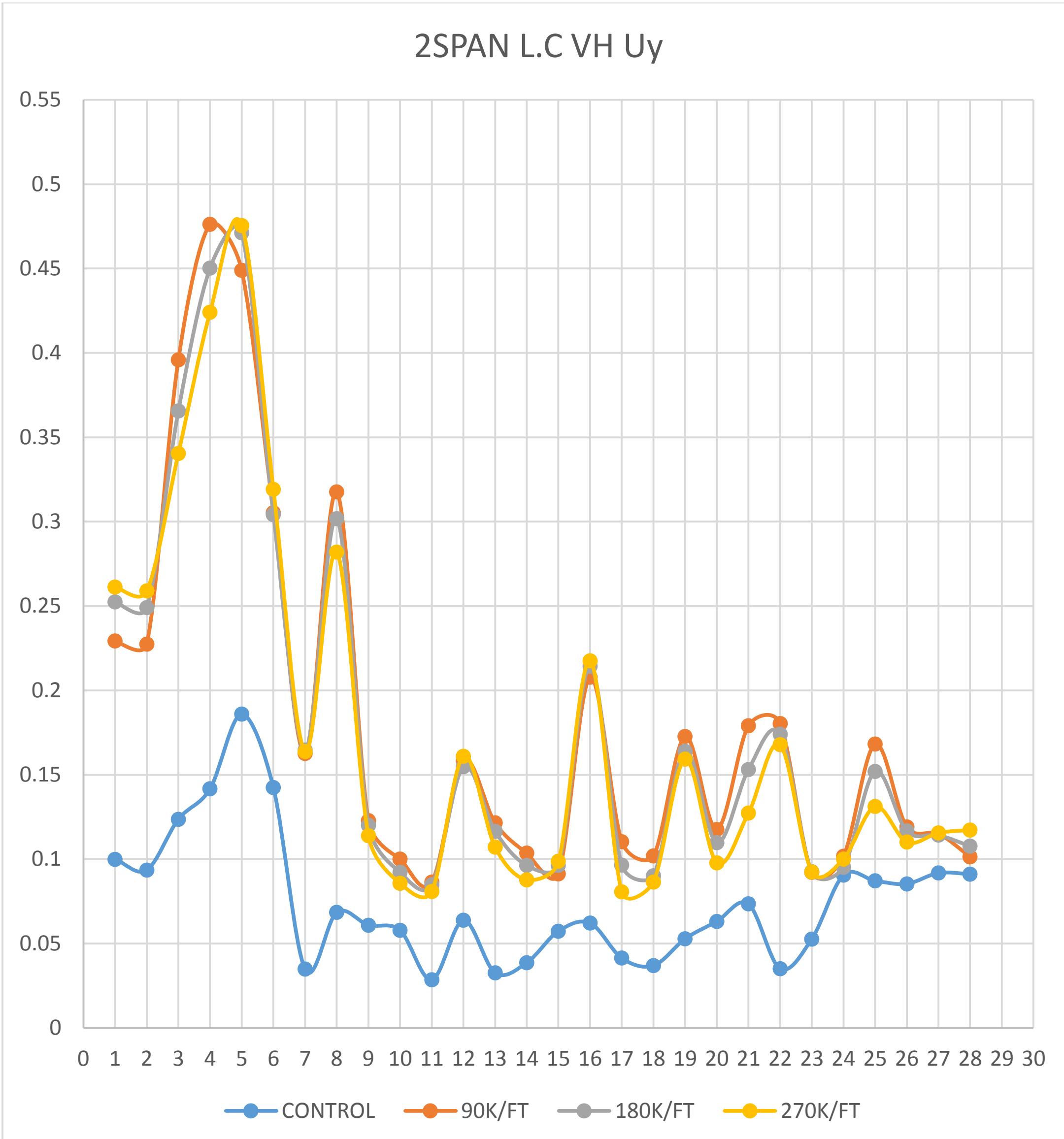


Fig. 3-24 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the two span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 2 span bridge show us that isolation stiffnesses of 180 and 270 can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 2 span bridge show us that 90, 180 and 270 kips per feet can be used as isolator stiffnesses without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 2 span bridge show us that for most earthquakes the displacements exceed the 2 feet limit, hence the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 3281.582

90 K/Ft = 1022.078

180 K/Ft = 1310.186

270 K/Ft = 1678.311

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

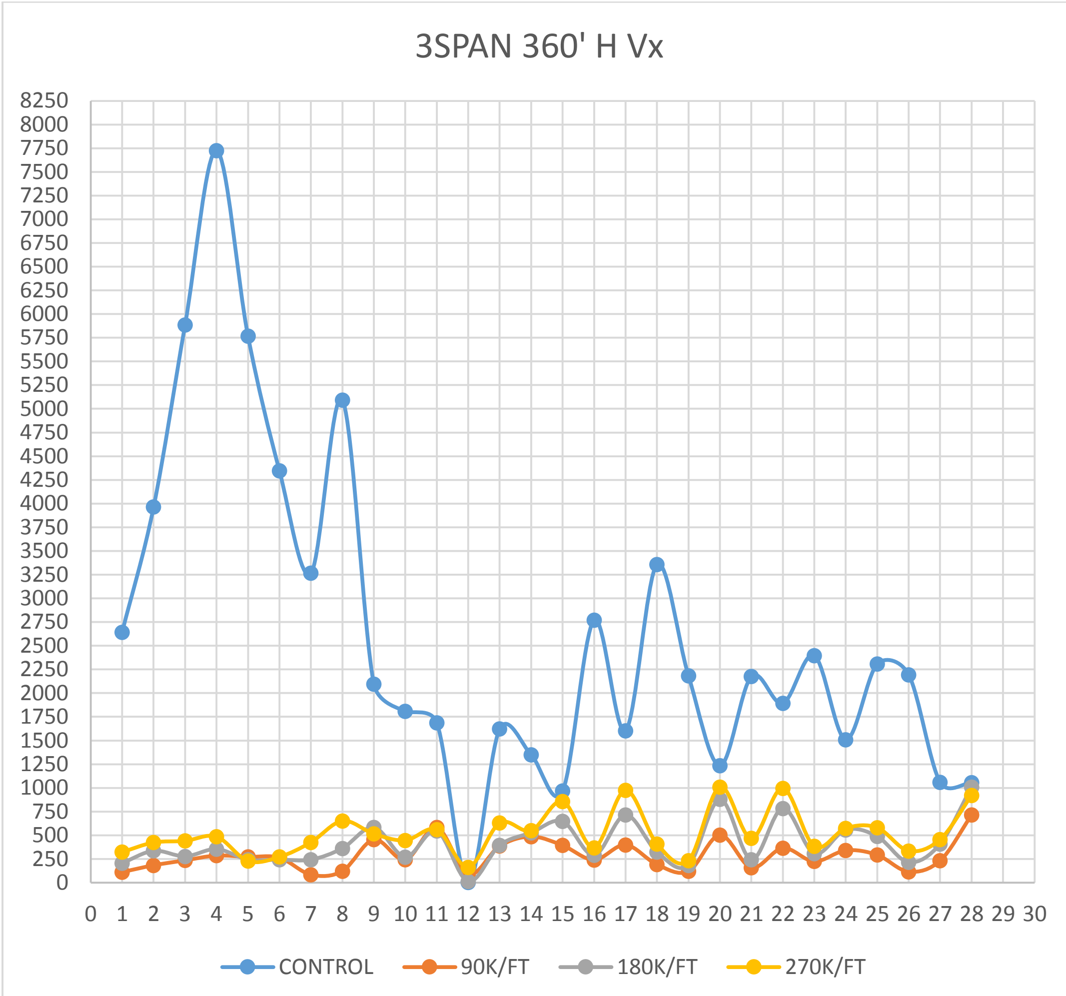


Fig. 3-25 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

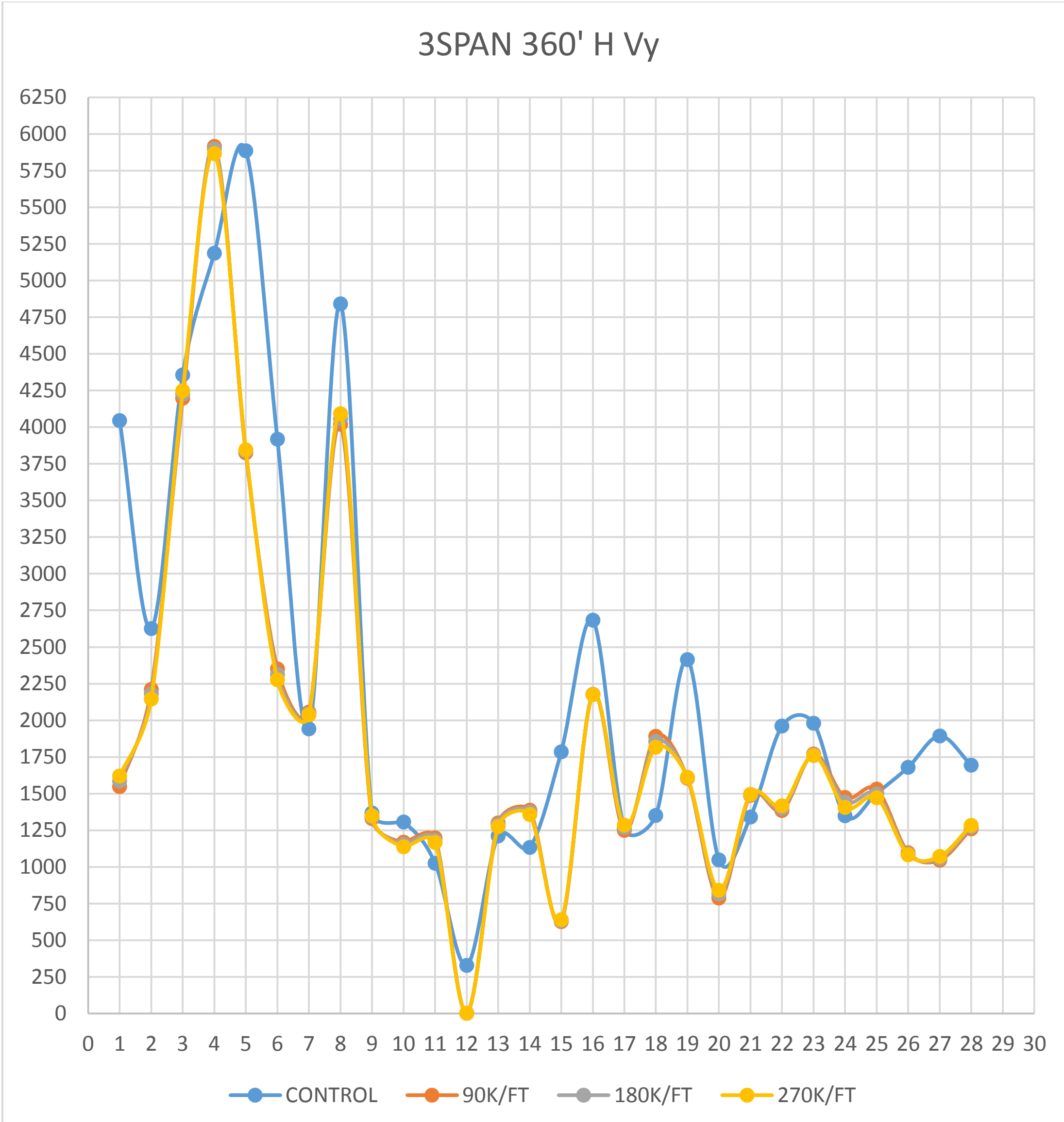


Fig. 3-26 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

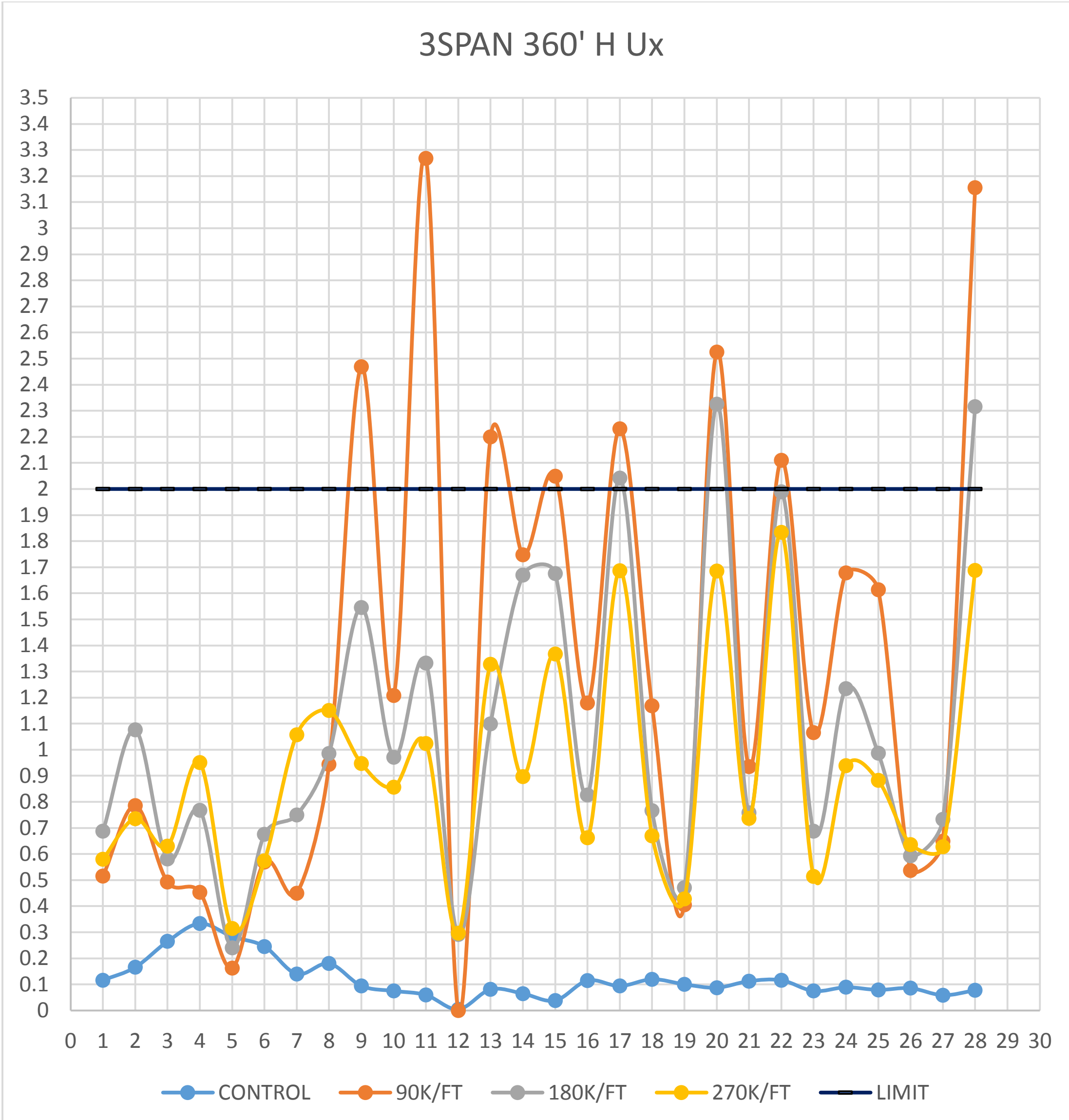


Fig. 3-27 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

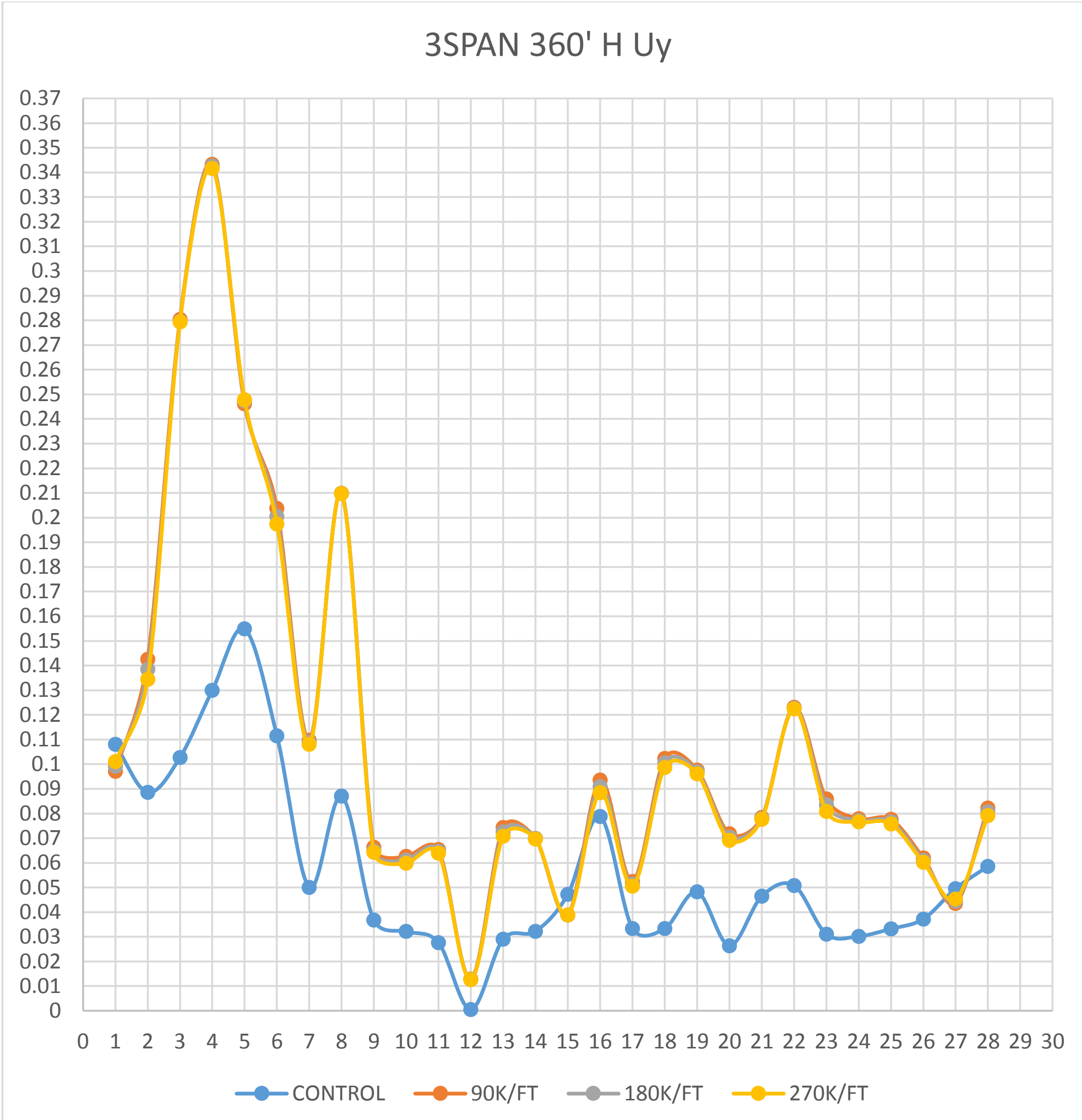


Fig. 3-28 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

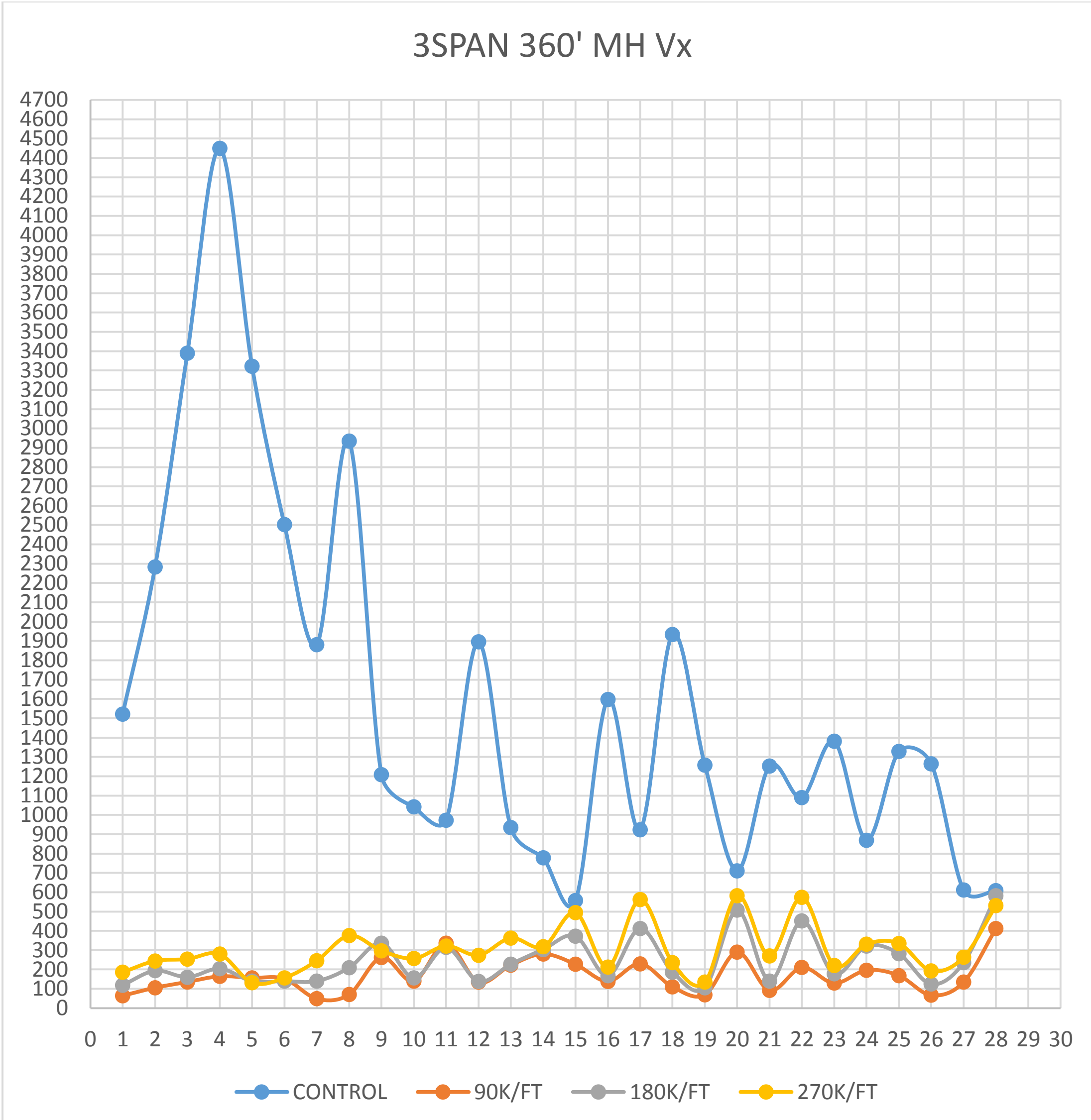


Fig. 3-29 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

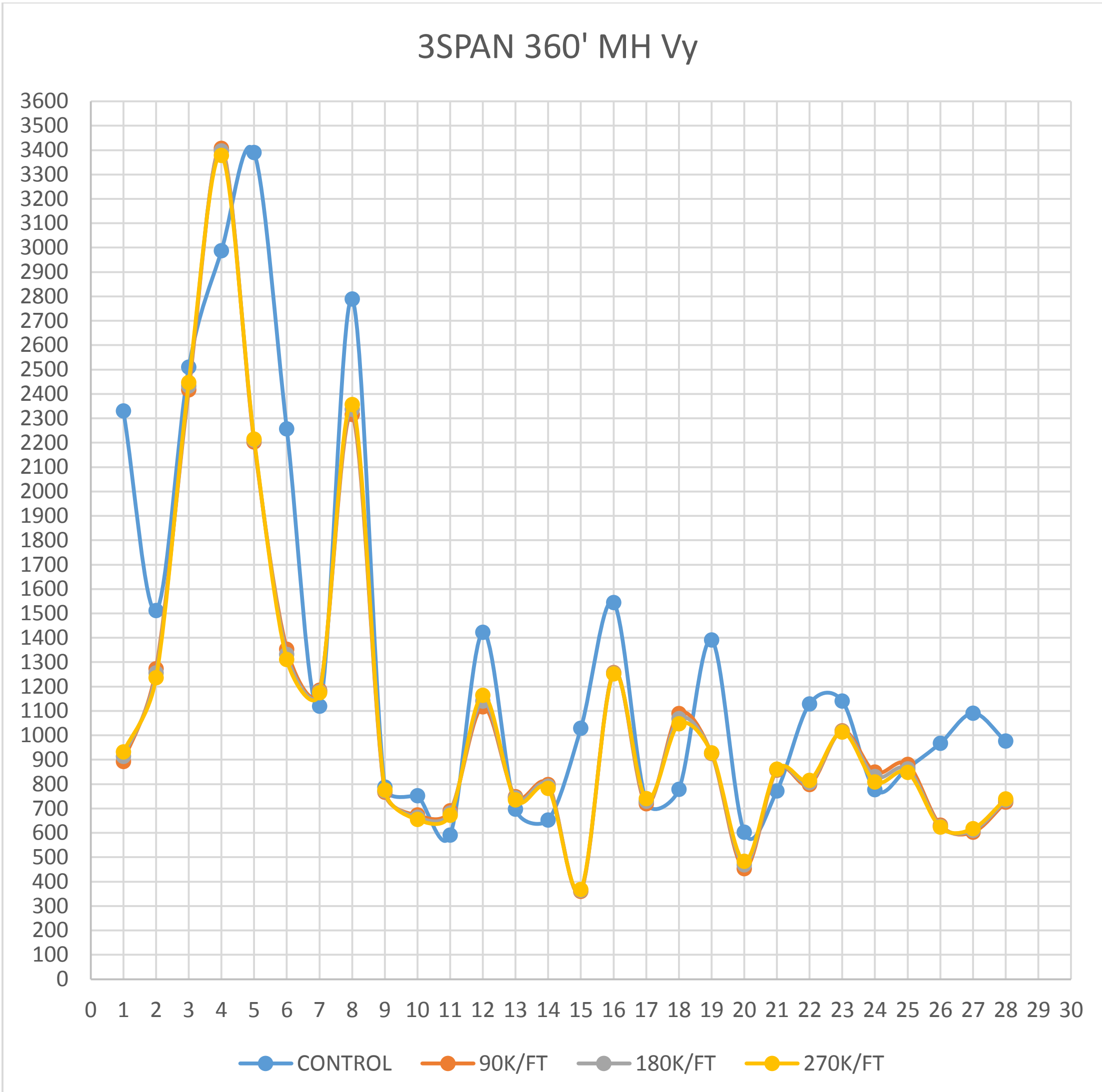


Fig. 3-30 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

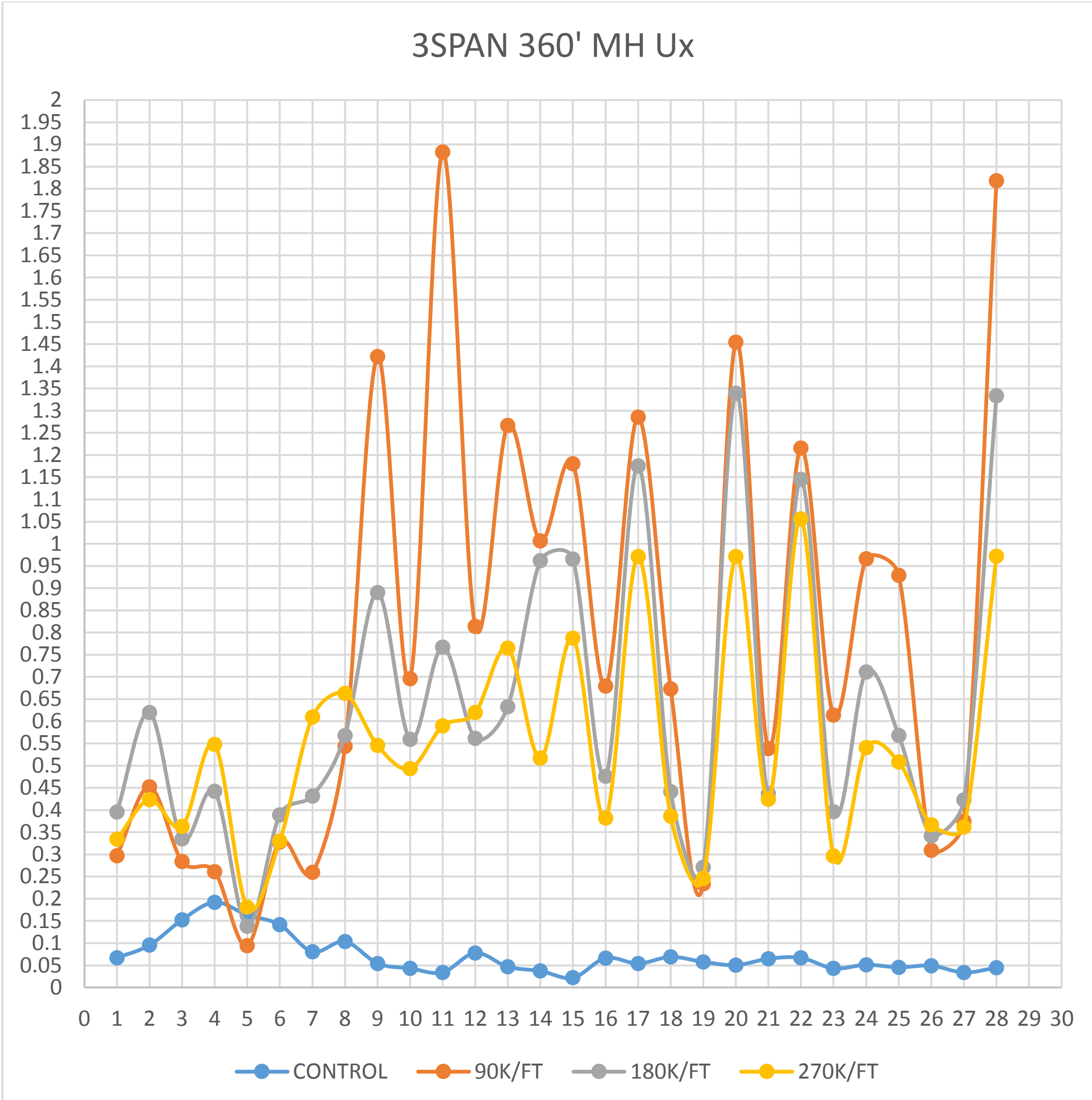


Fig. 3-31 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

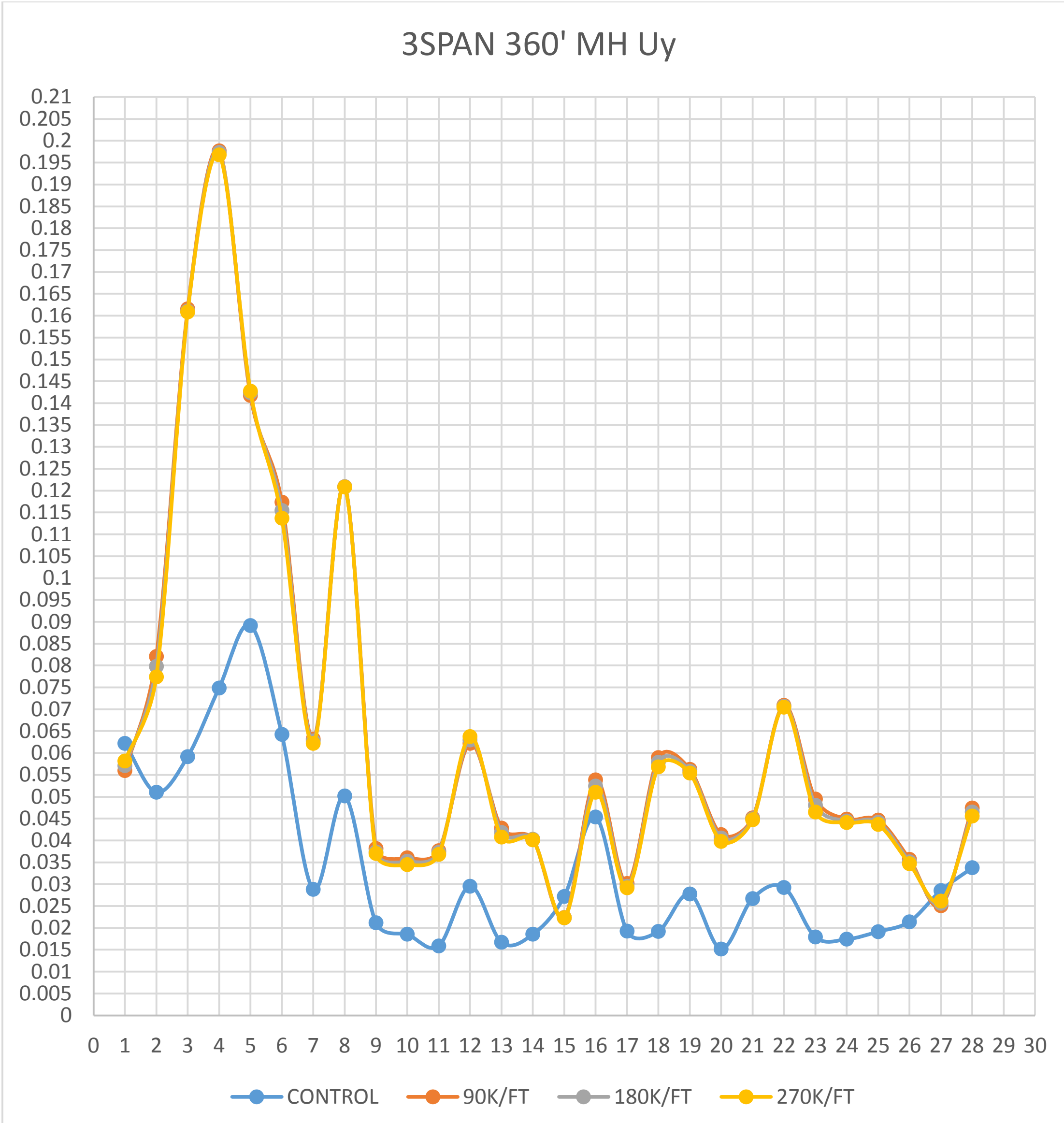


Fig. 3-32 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

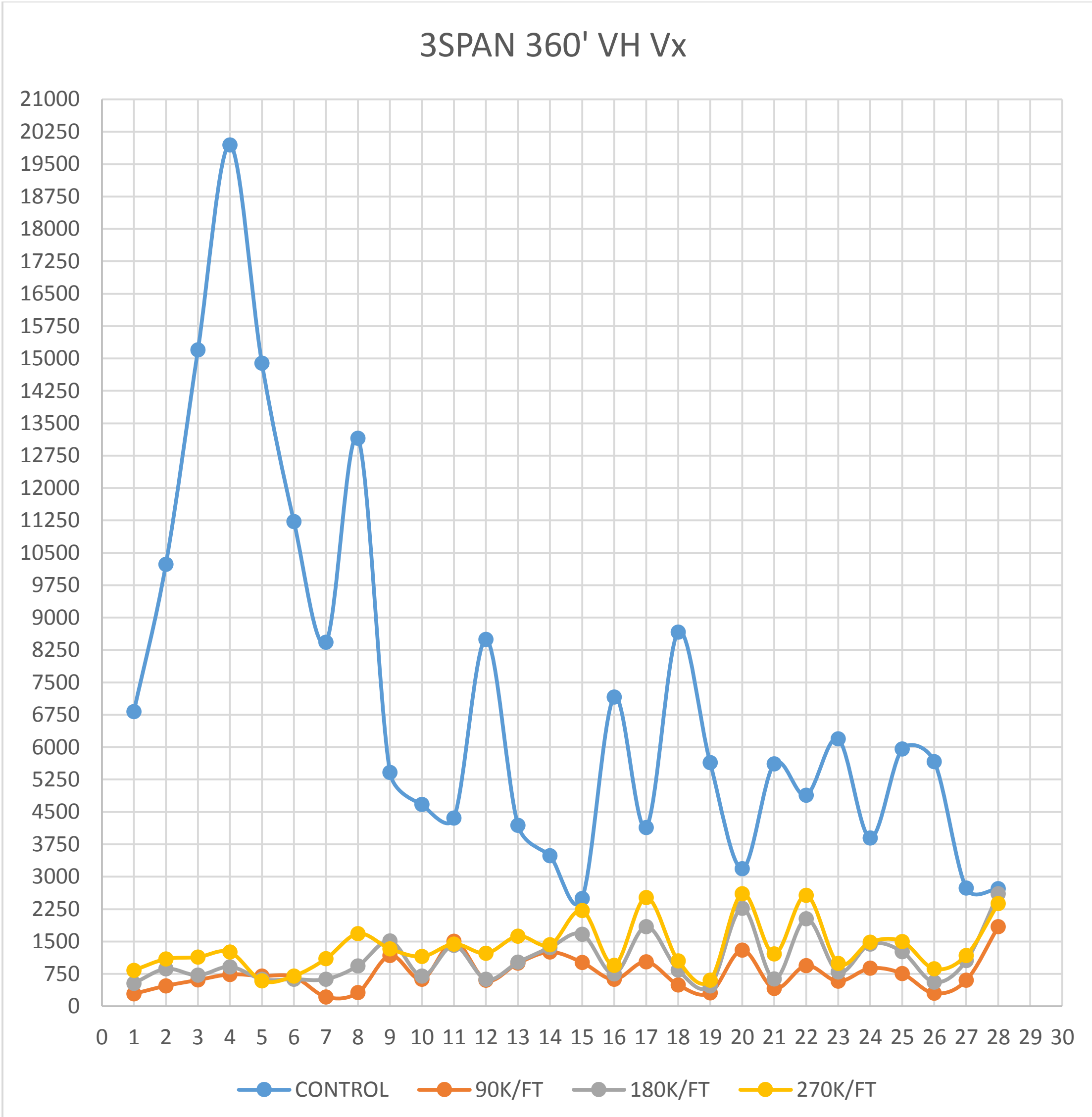


Fig. 3-33 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

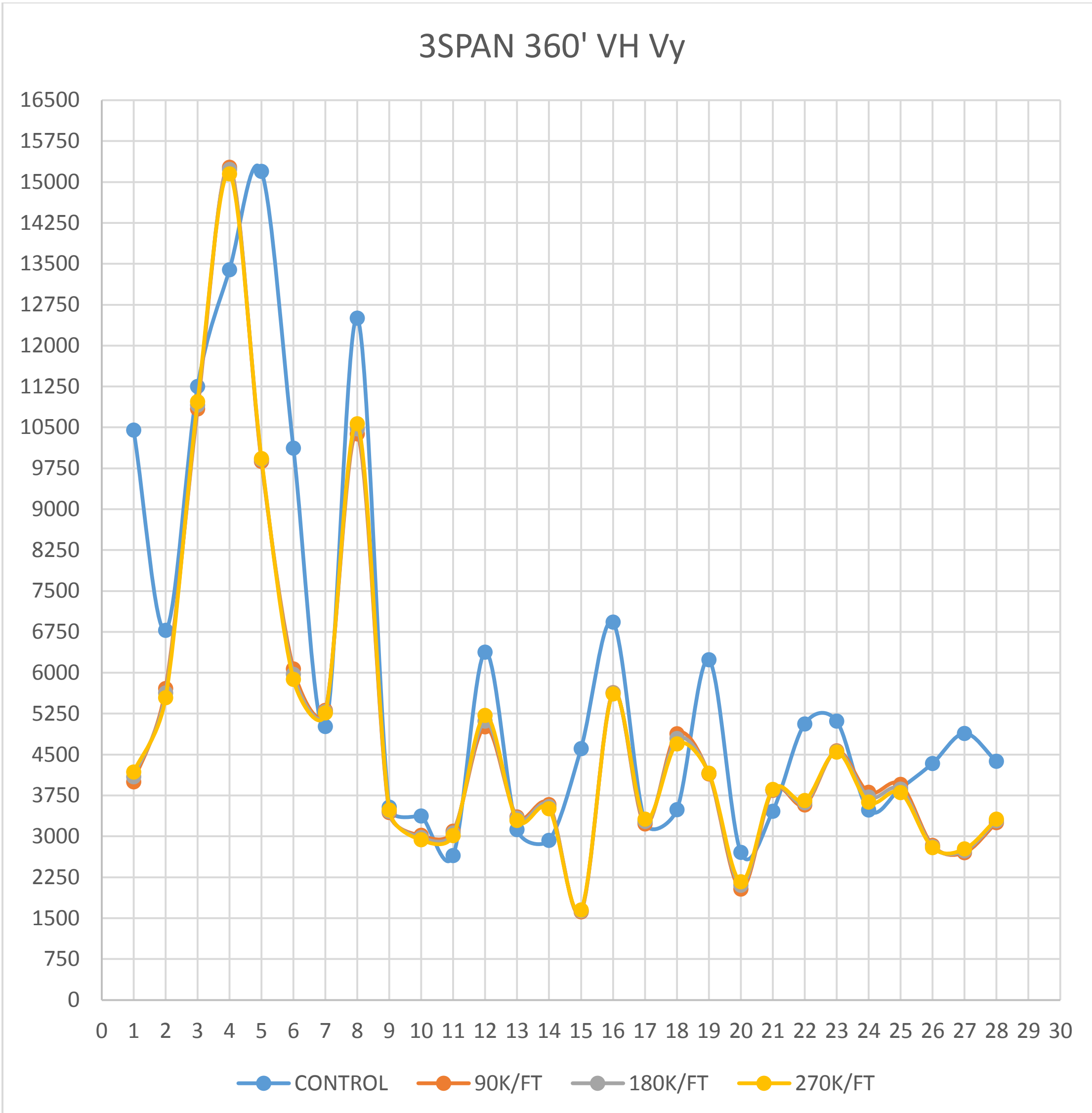


Fig. 3-34 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

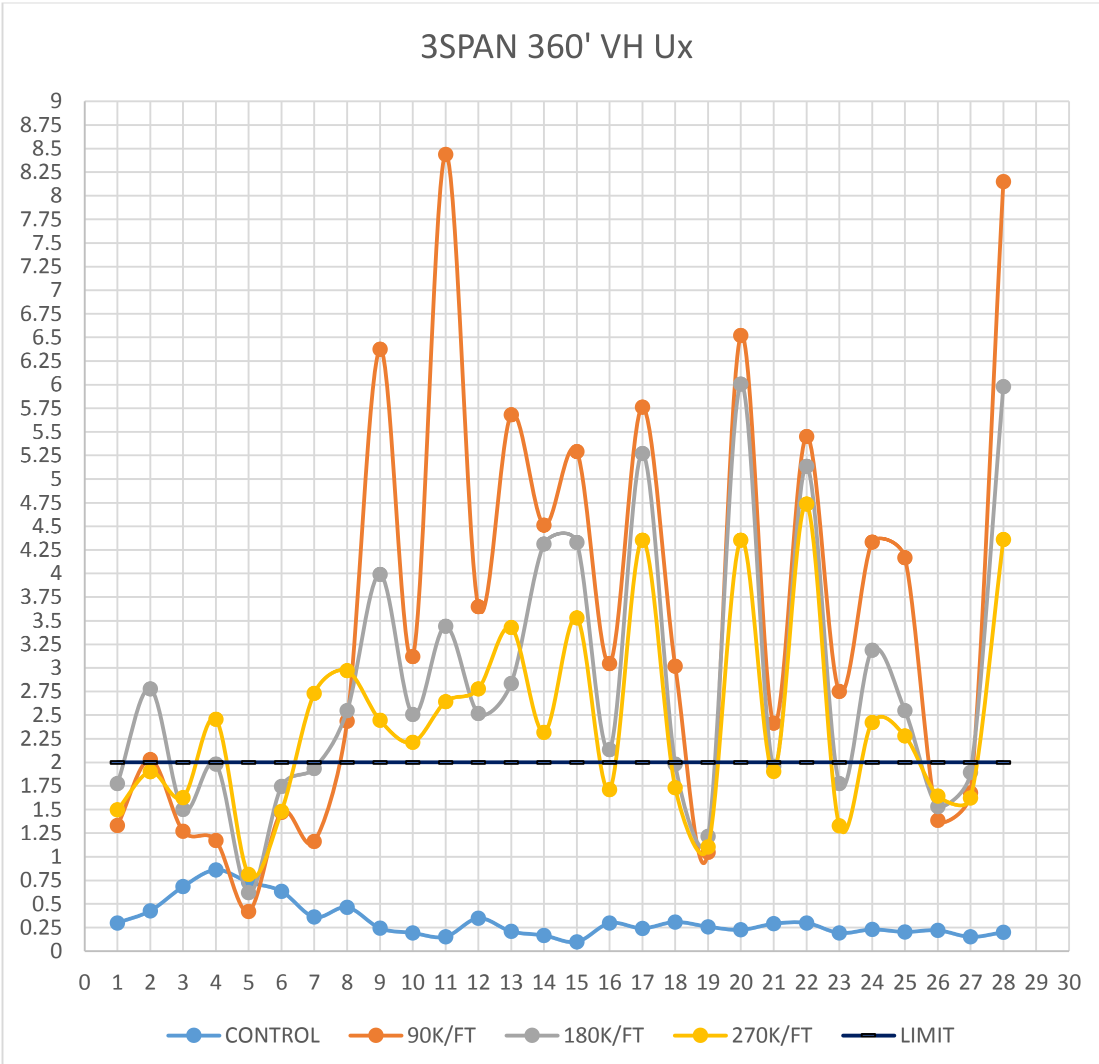


Fig. 3-35 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

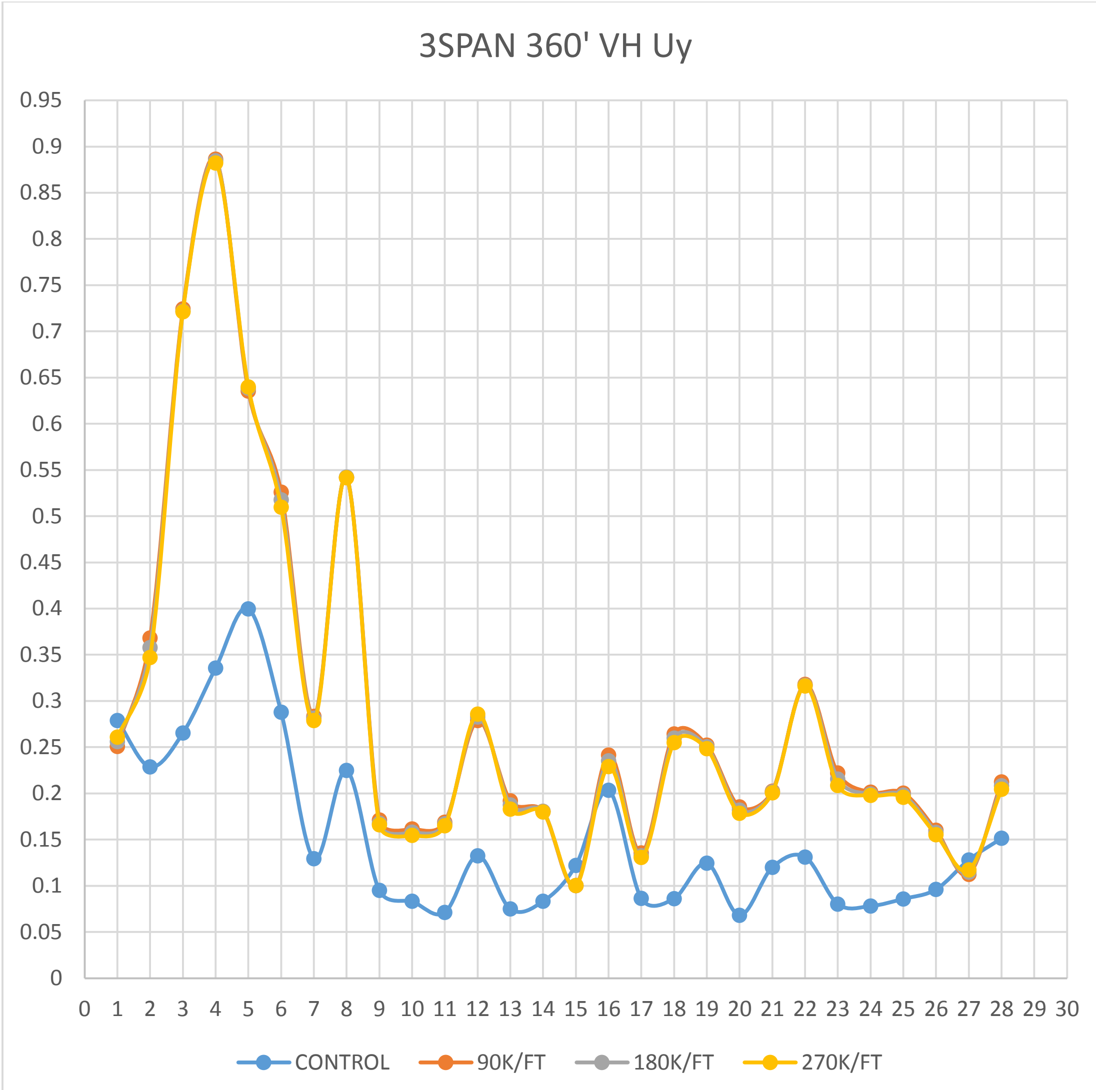


Fig. 3-36 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that stiffness values of 90, 180 and 270 kips per feet can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 19947.71

90 K/Ft = 1843.225

180 K/Ft = 2605.66

270 K/Ft = 2607.083

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

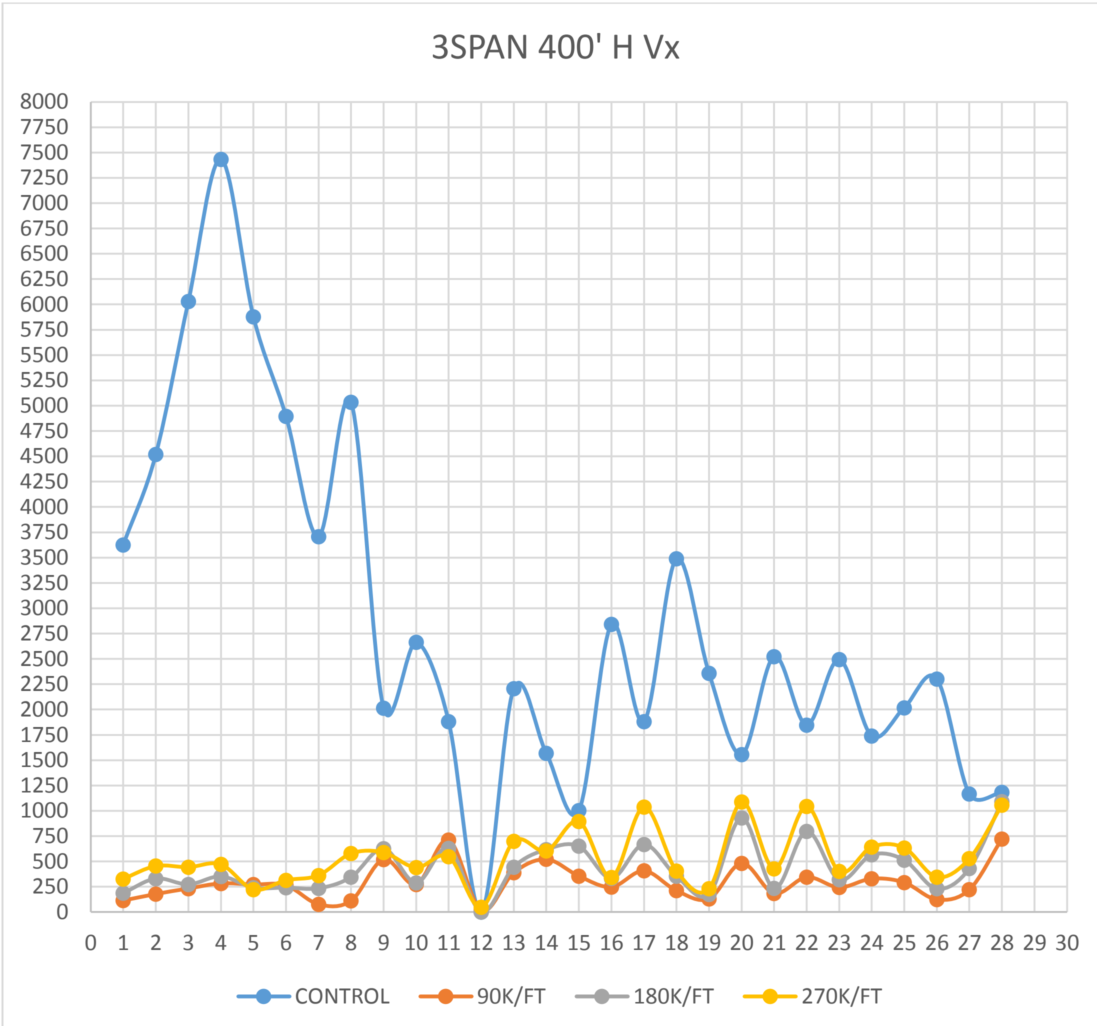


Fig. 3-37 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

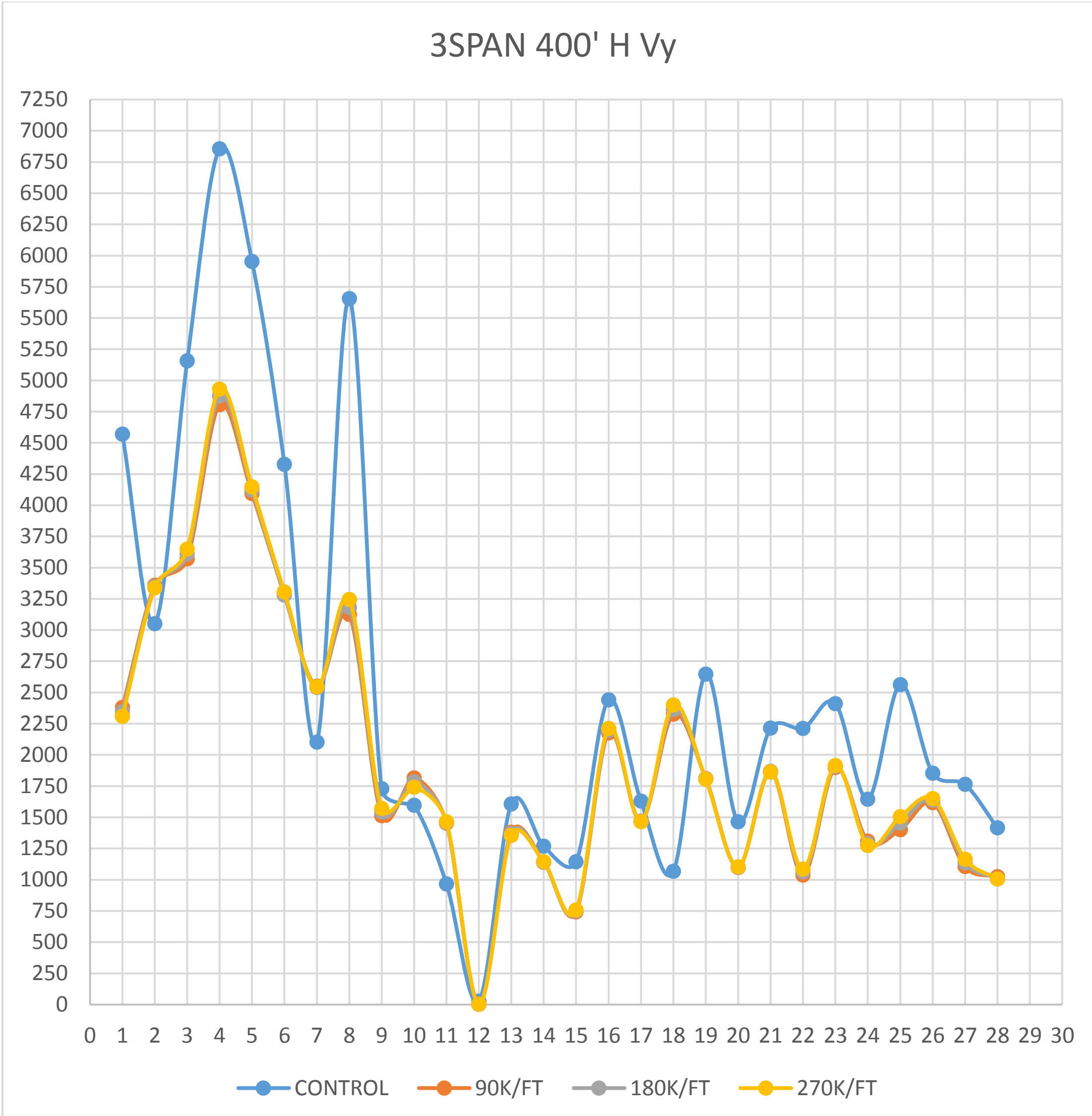


Fig. 3-38 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

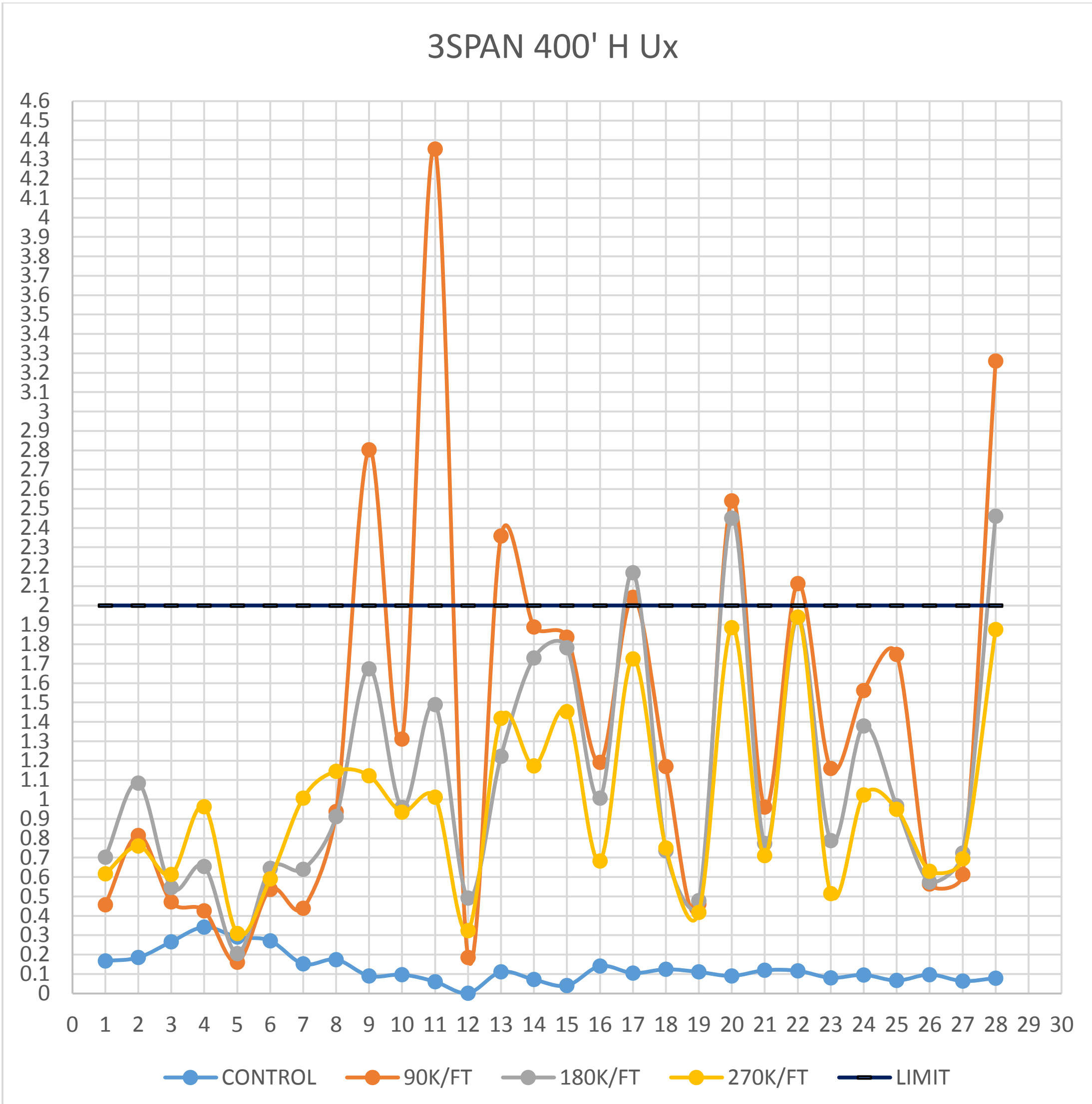


Fig. 3-39 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

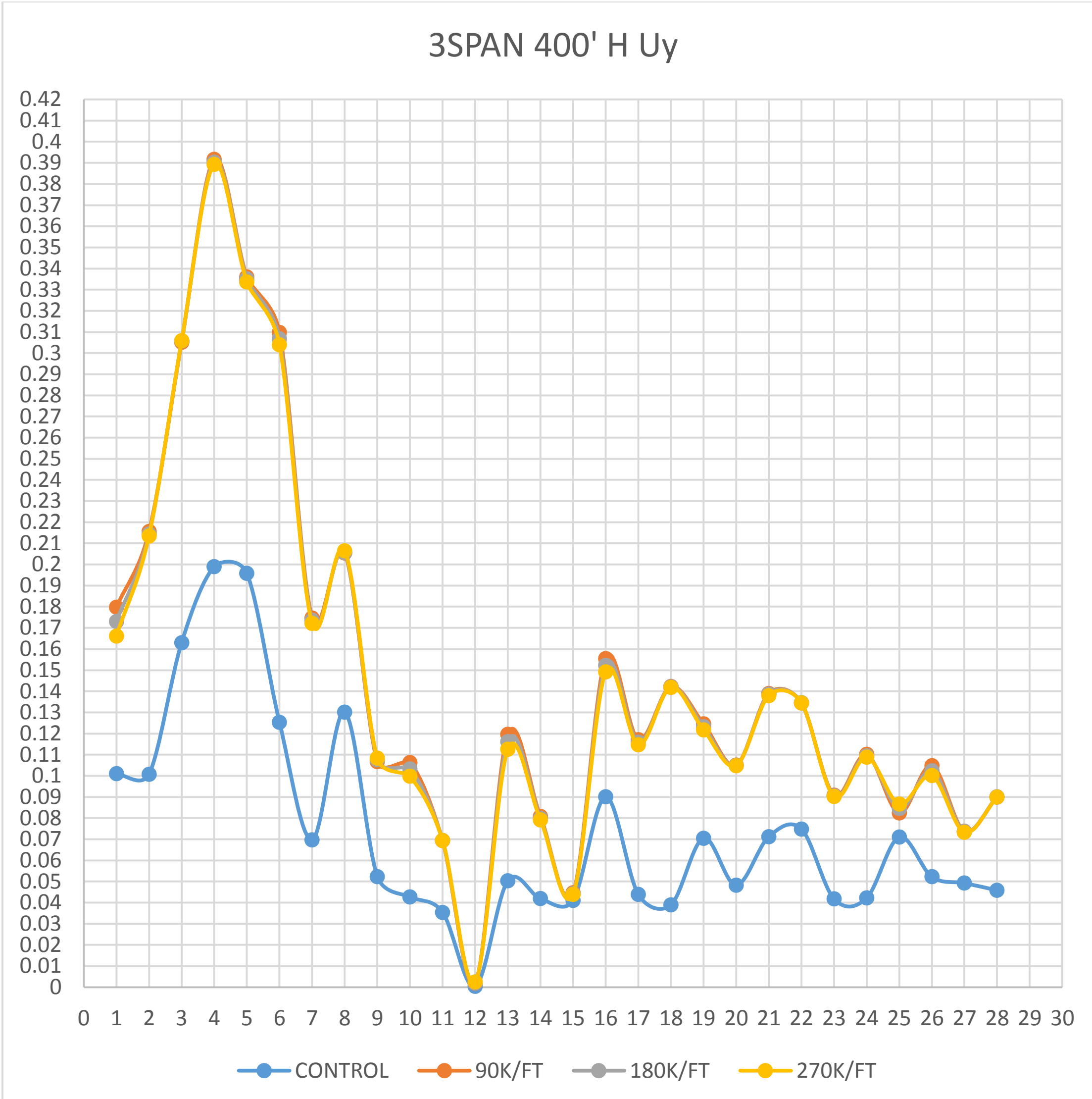


Fig. 3-40 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

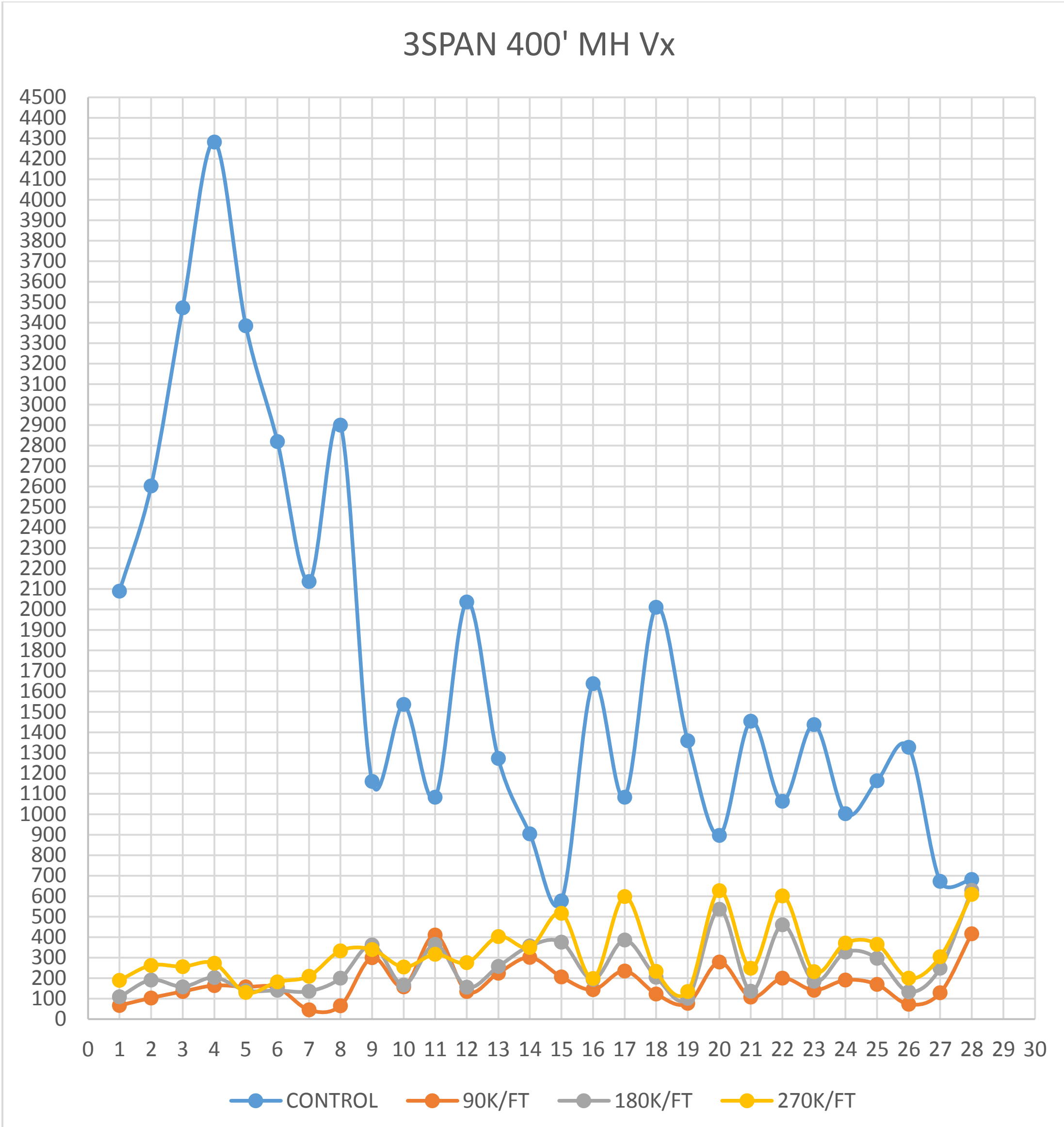


Fig. 3-41 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

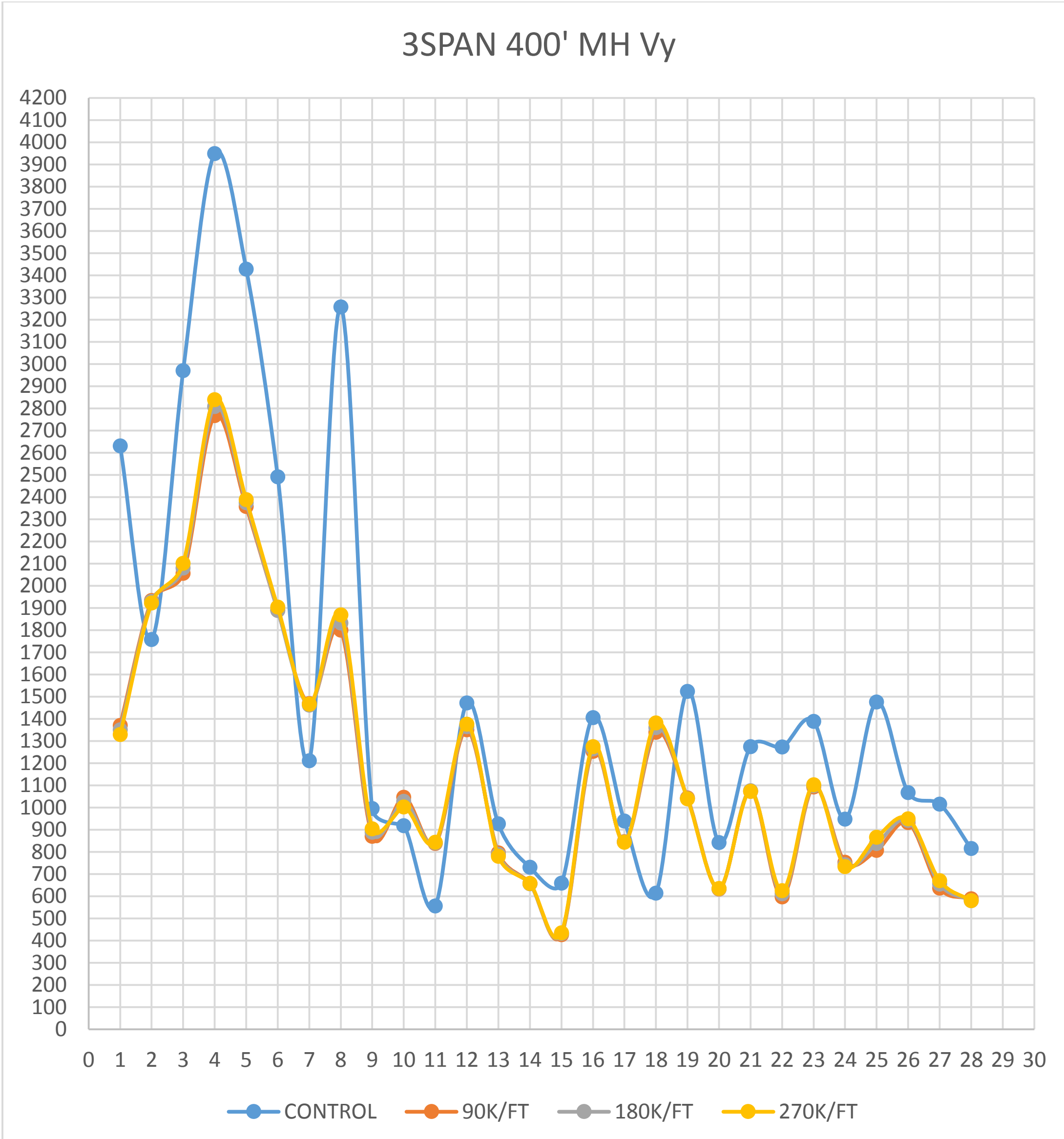


Fig. 3-42 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

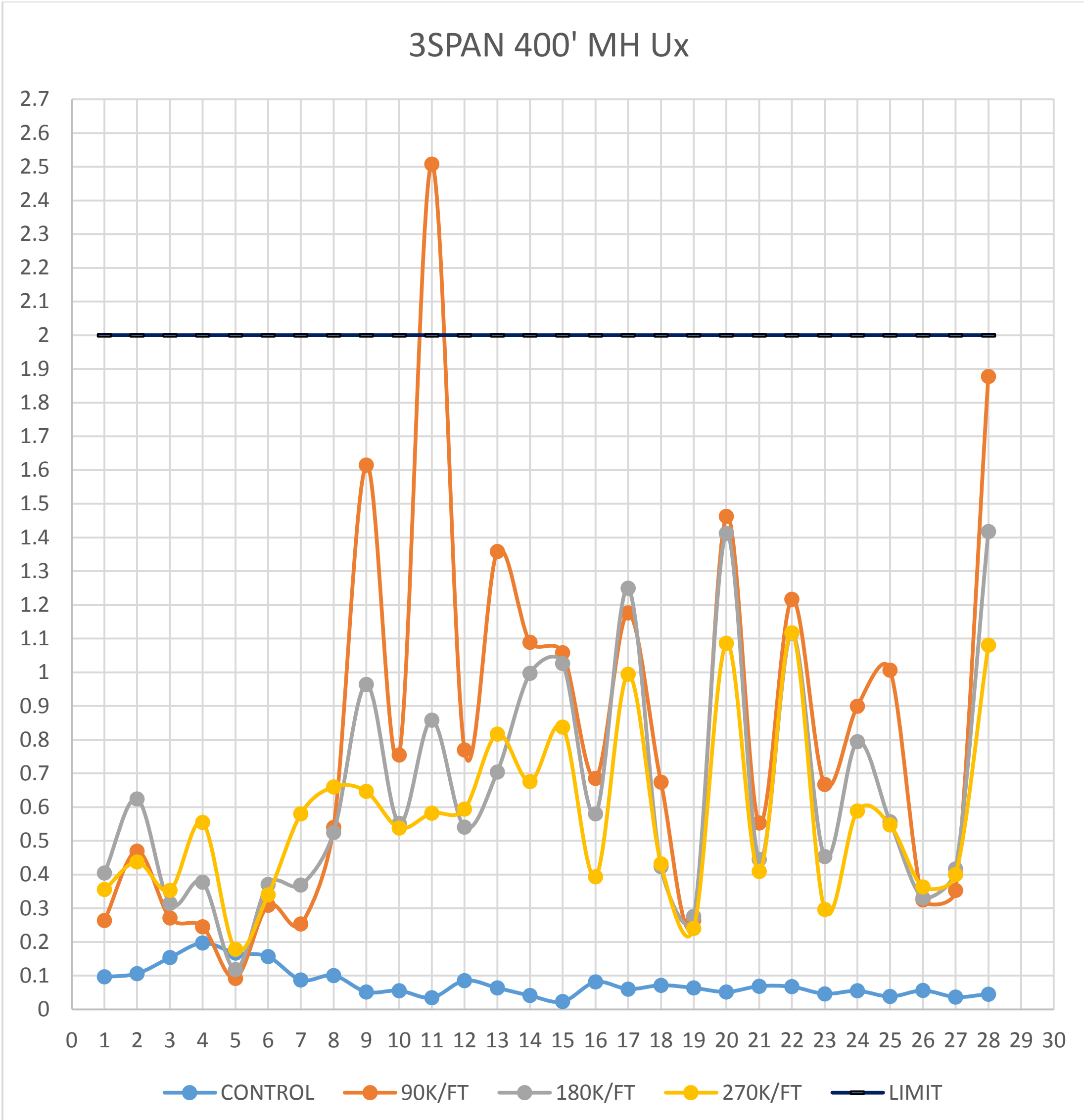


Fig. 3-43 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

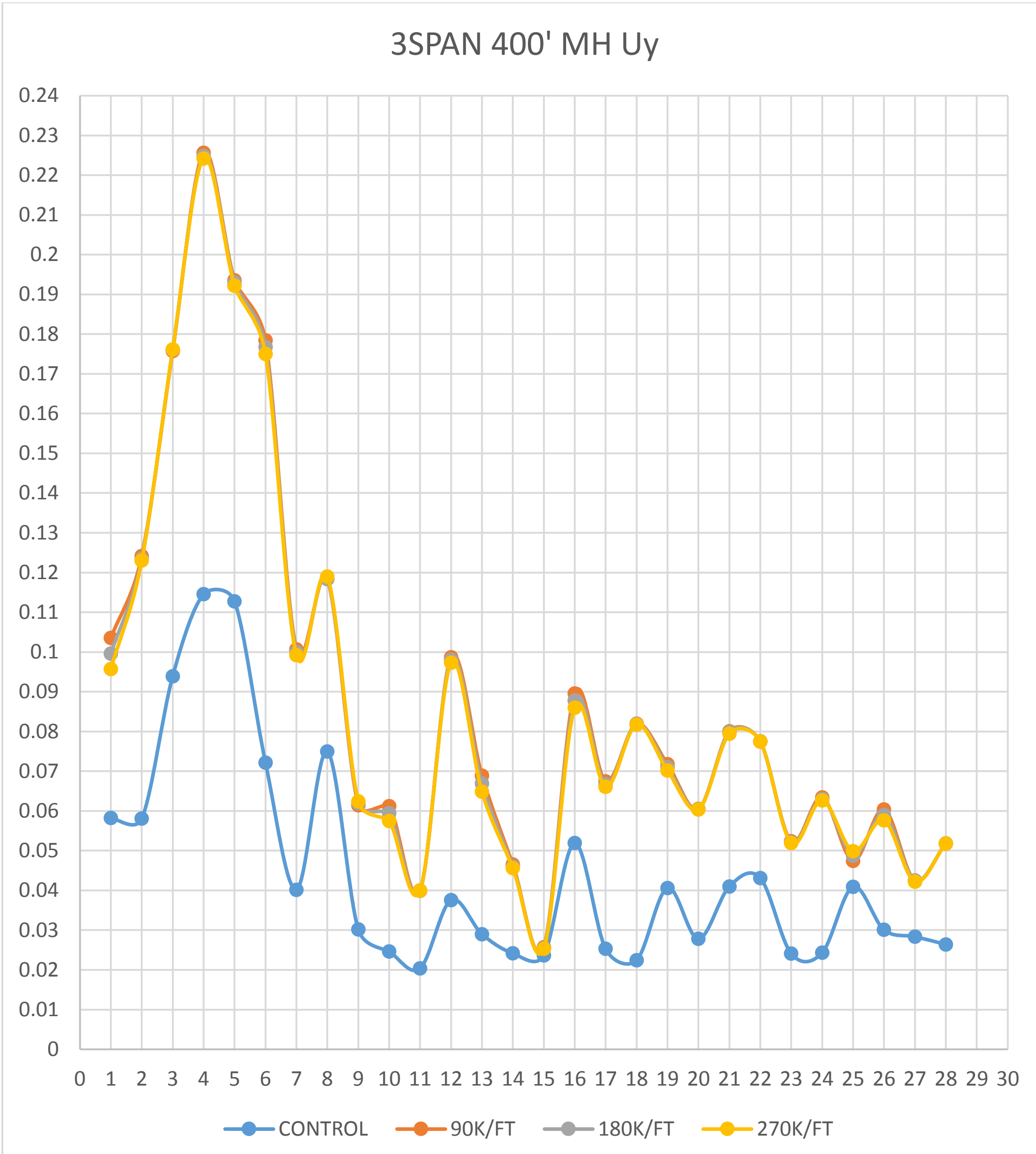


Fig. 3-44 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

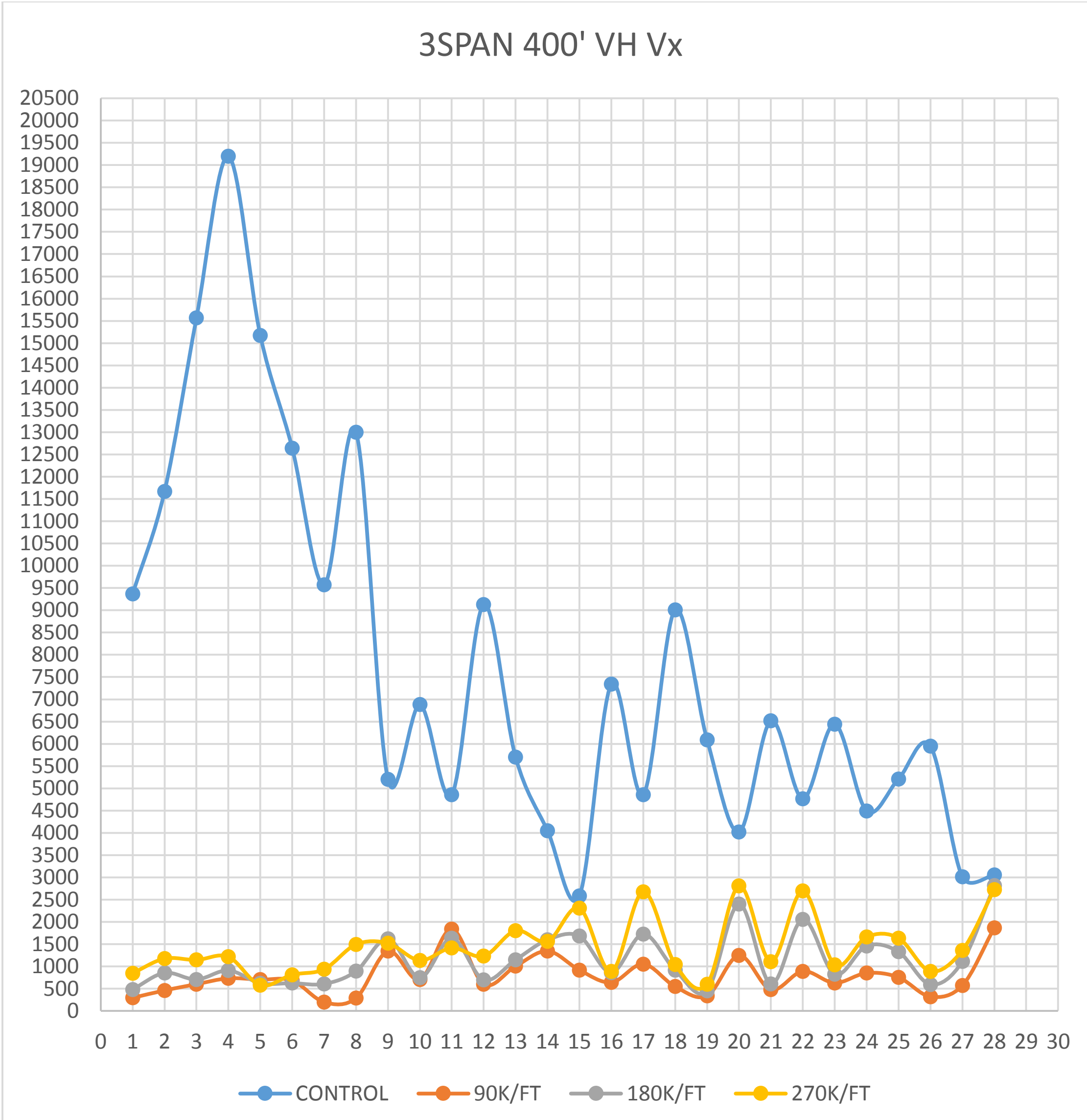


Fig. 3-45 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

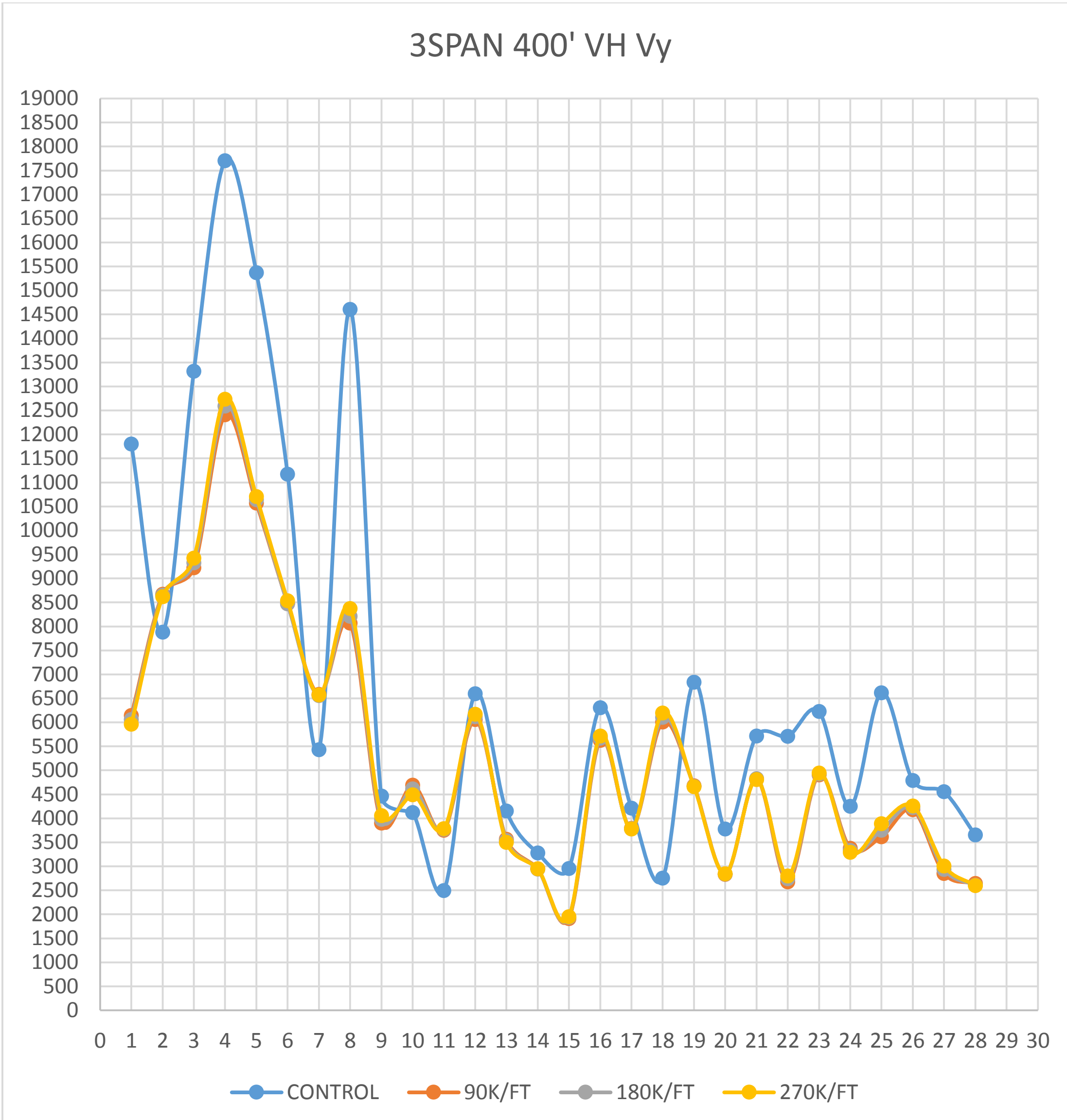


Fig. 3-46 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

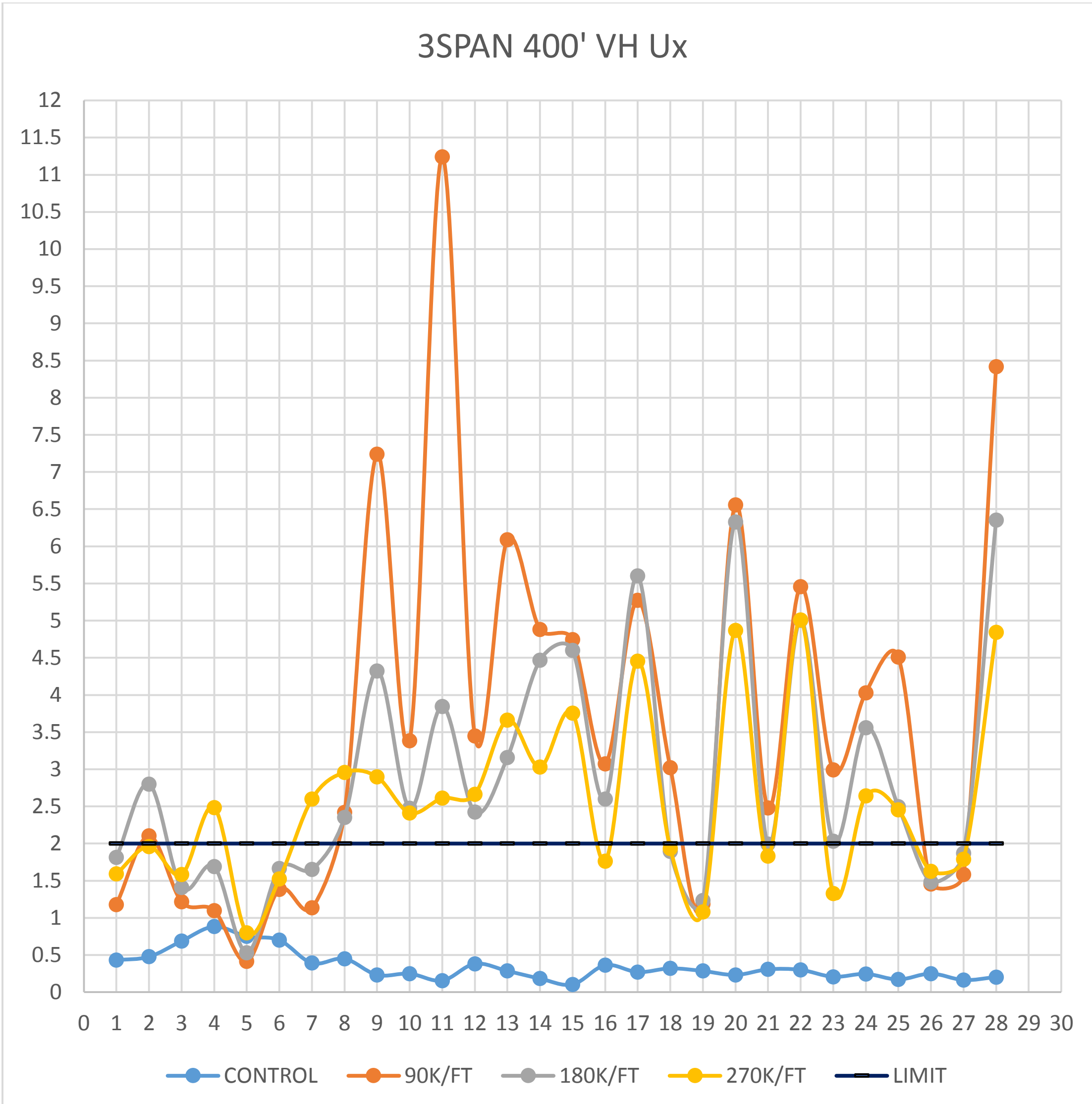


Fig. 3-47 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

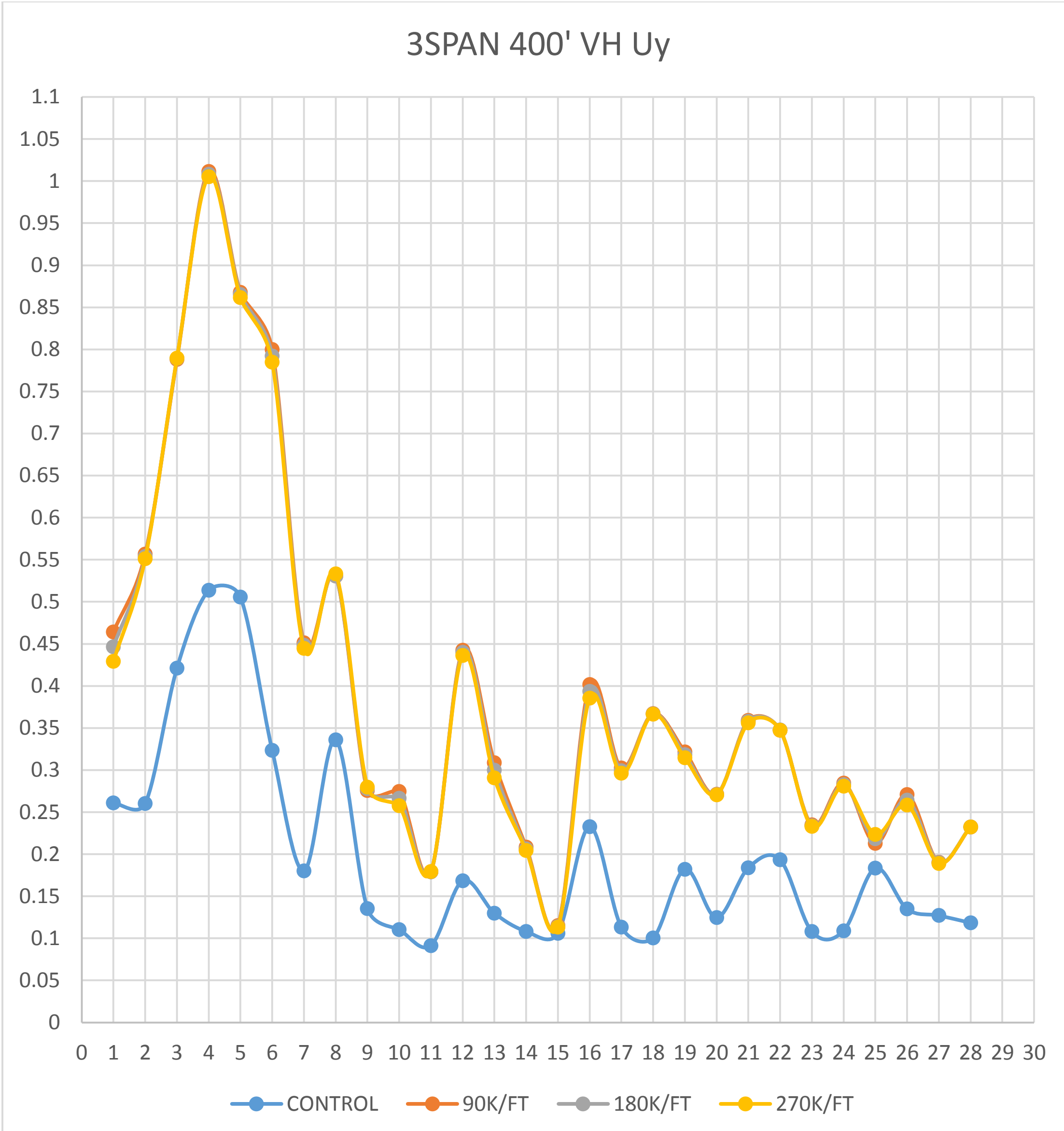


Fig. 3-48 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that all three isolation stiffnesses can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 19196.68

90 K/Ft = 1867.582

180 K/Ft = 2815.389

270 K/Ft = 2807.748

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

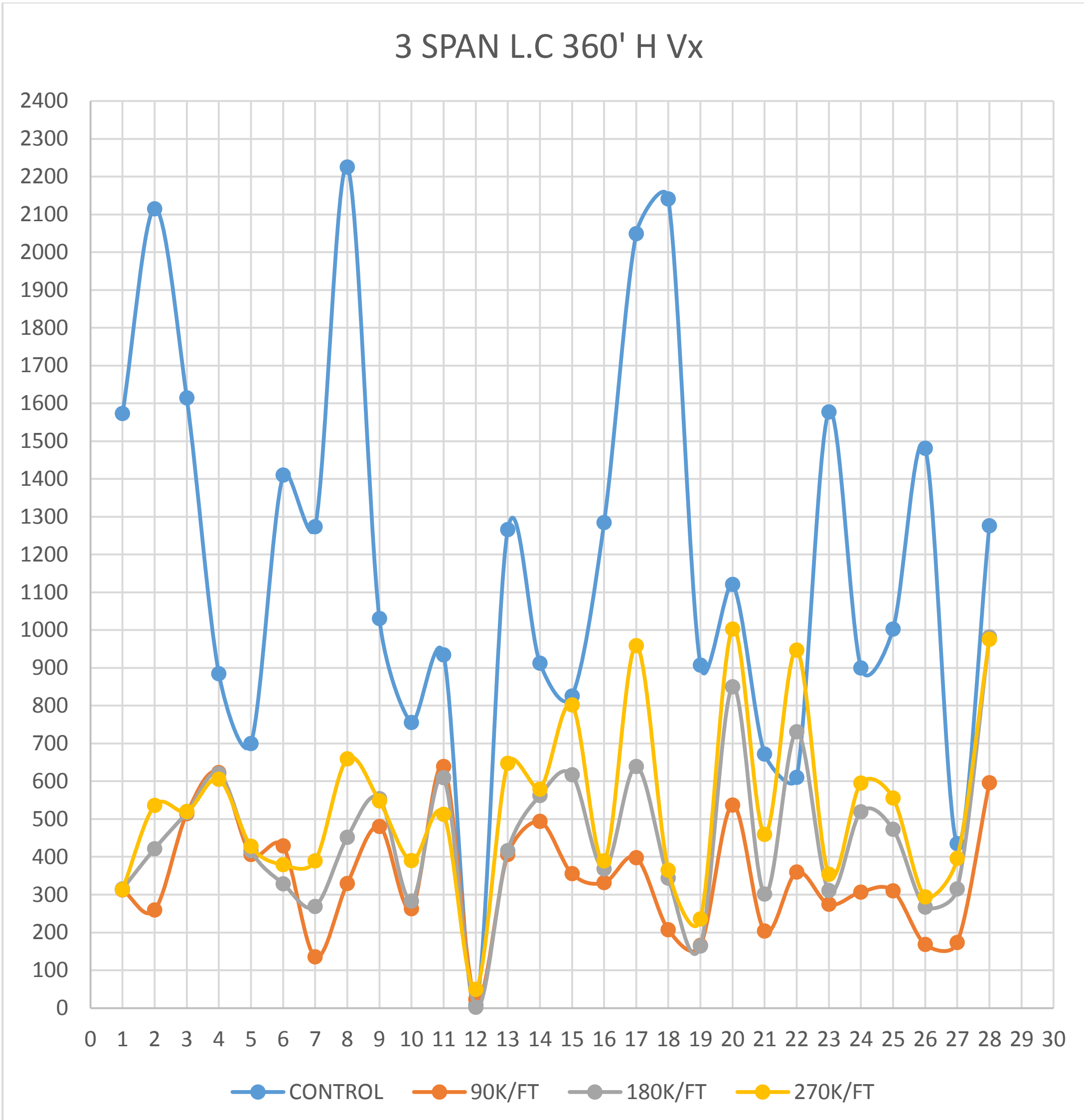


Fig. 3-49 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

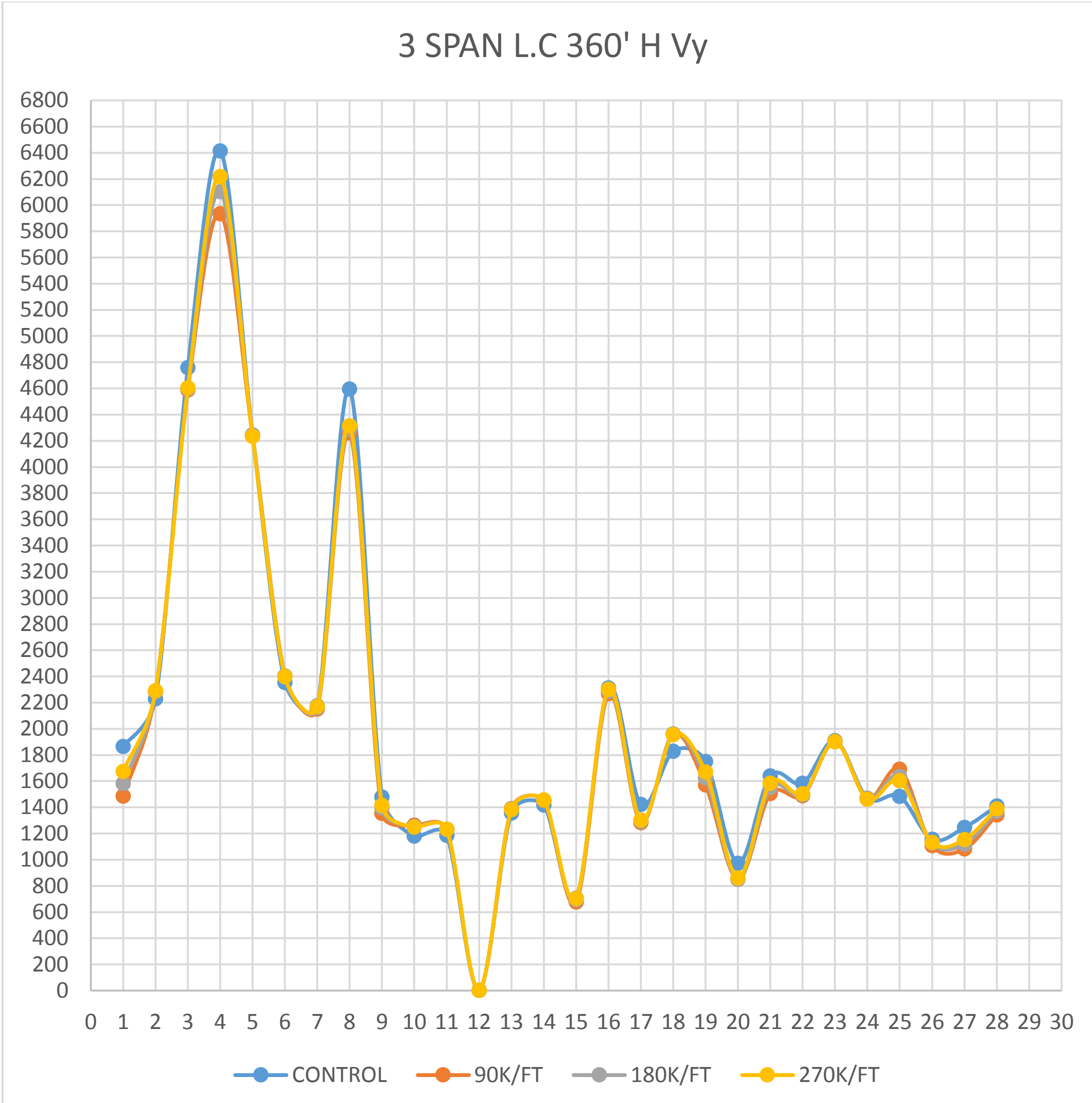


Fig. 3-50 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

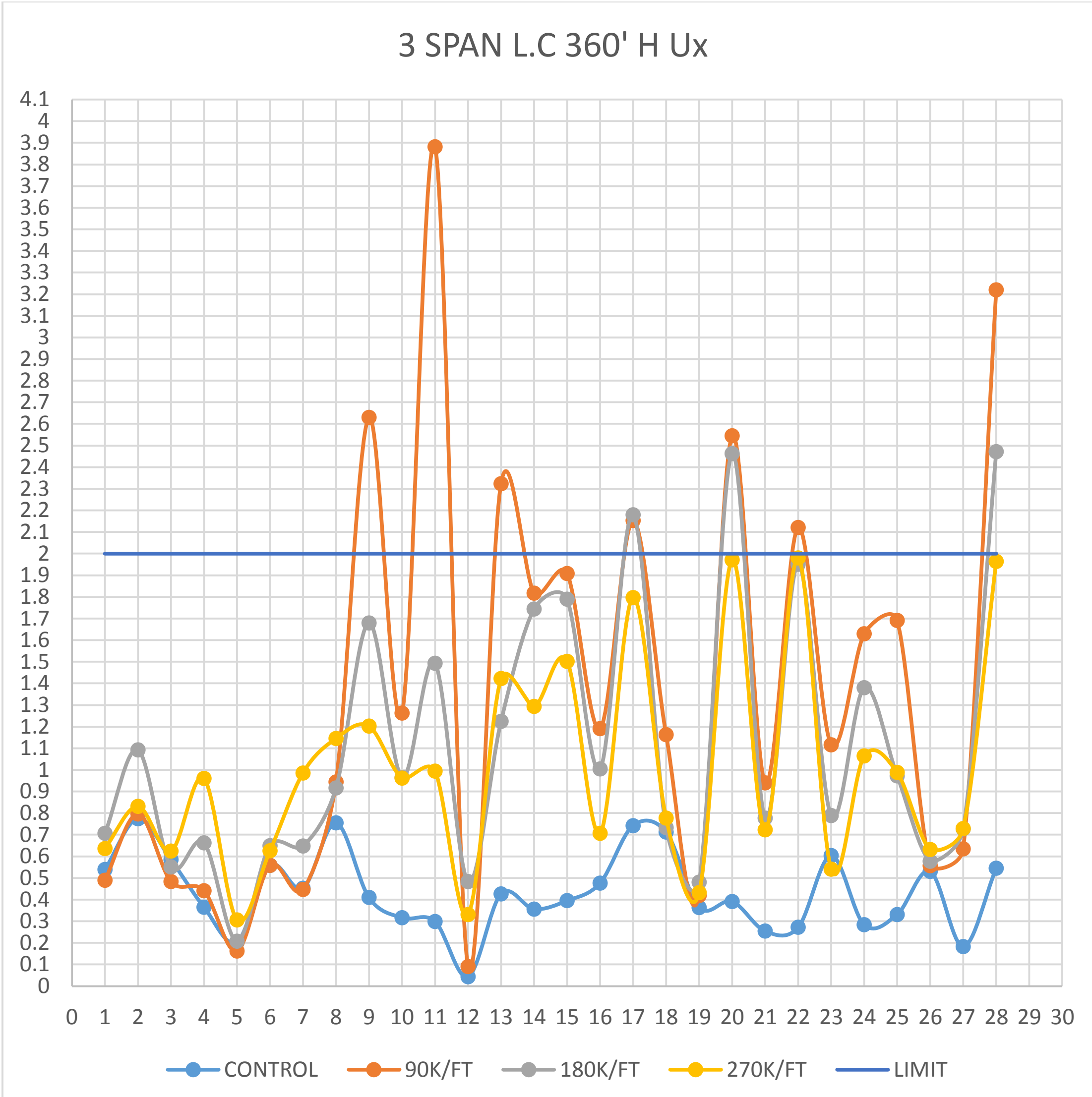


Fig. 3-51 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

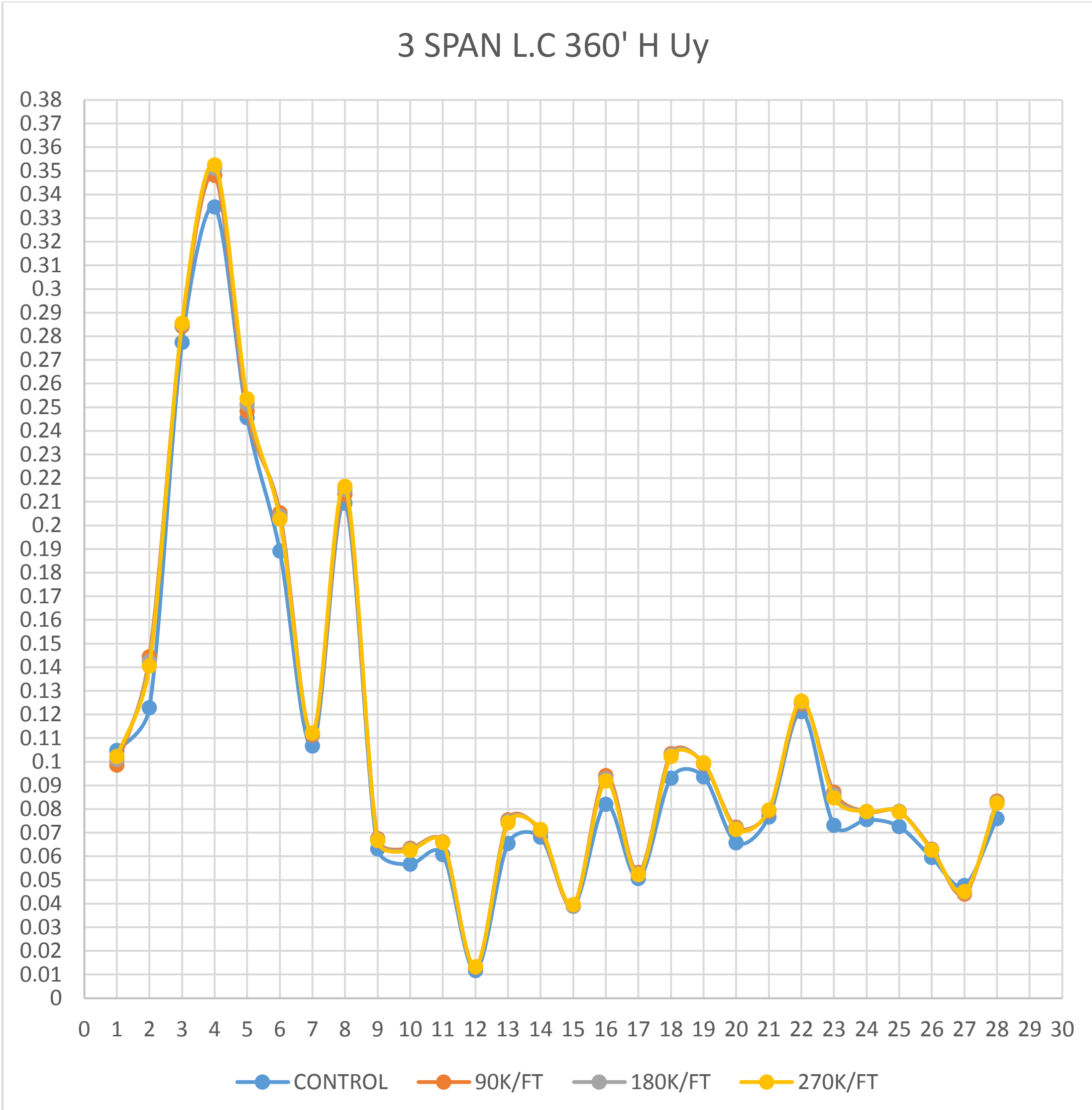


Fig. 3-52 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

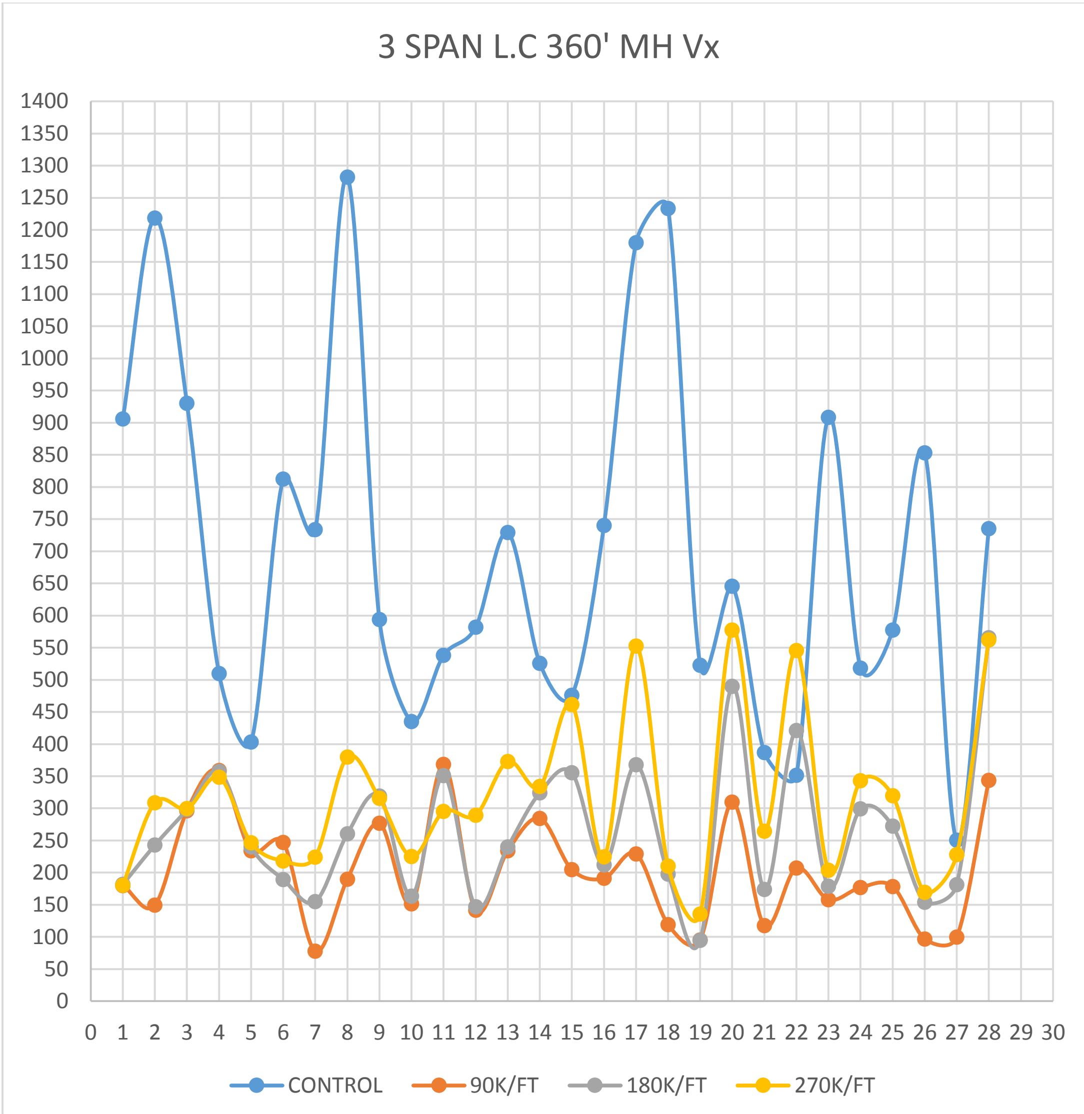


Fig. 3-53 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

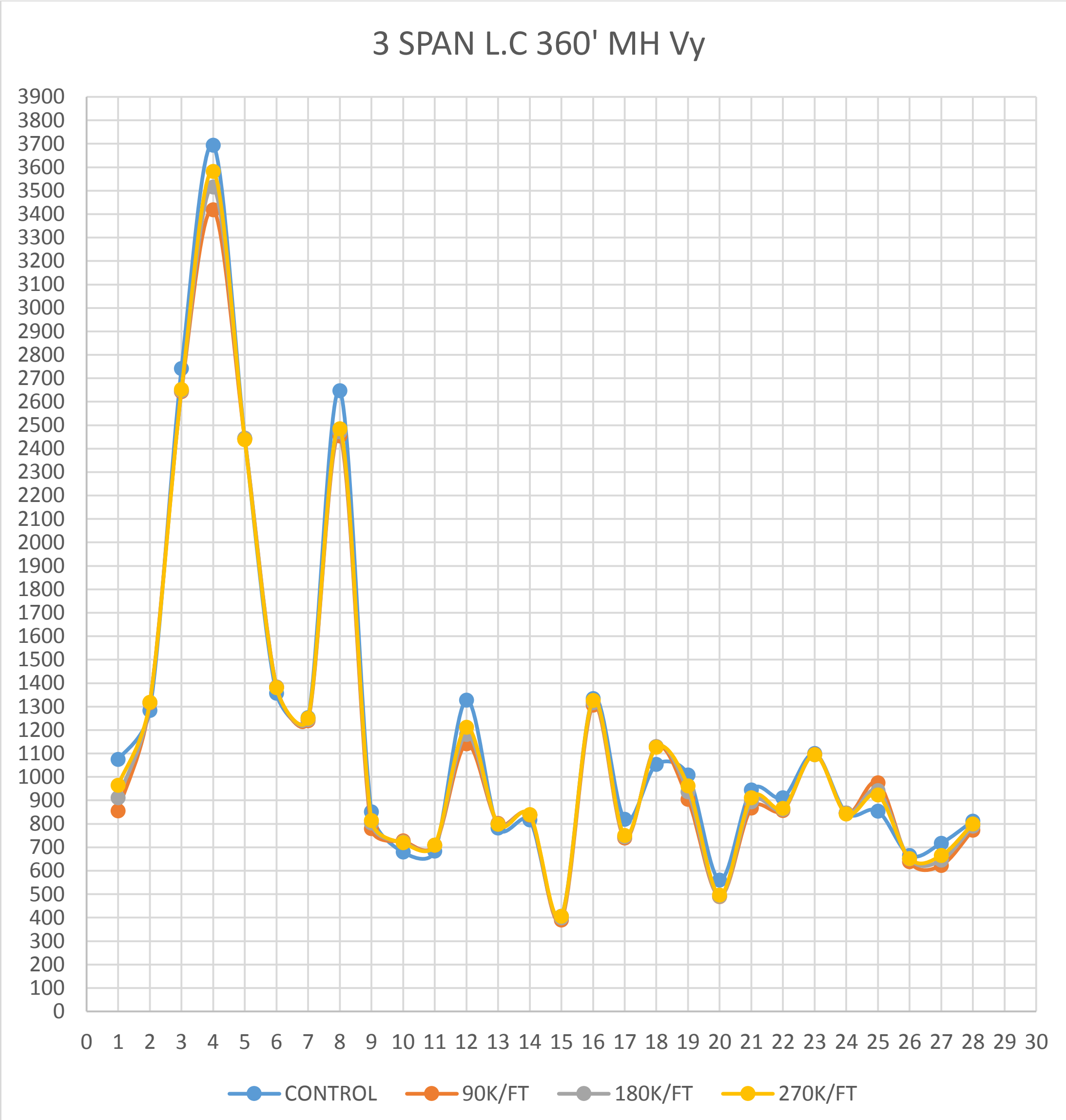


Fig. 3-54 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

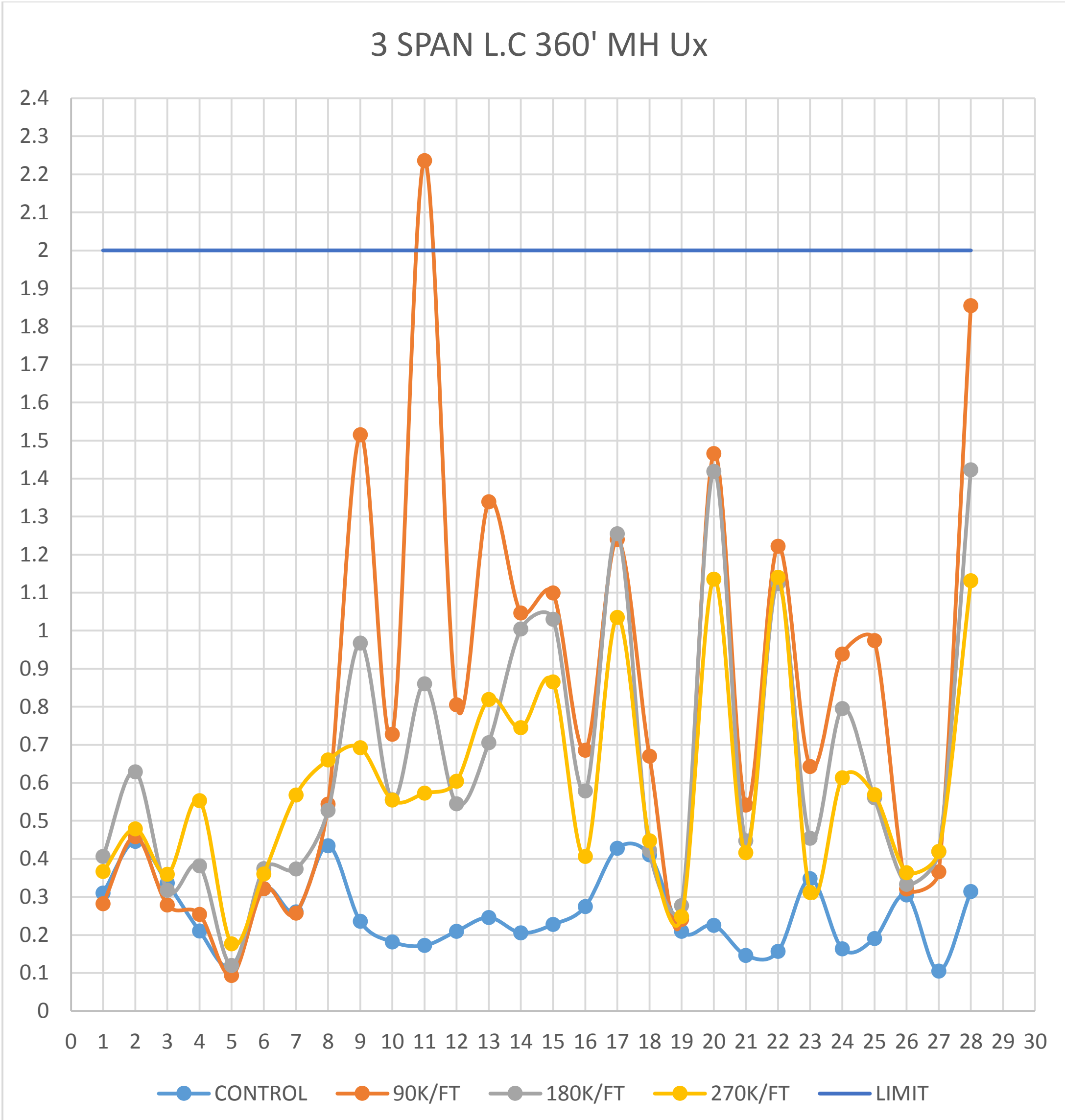


Fig. 3-55 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

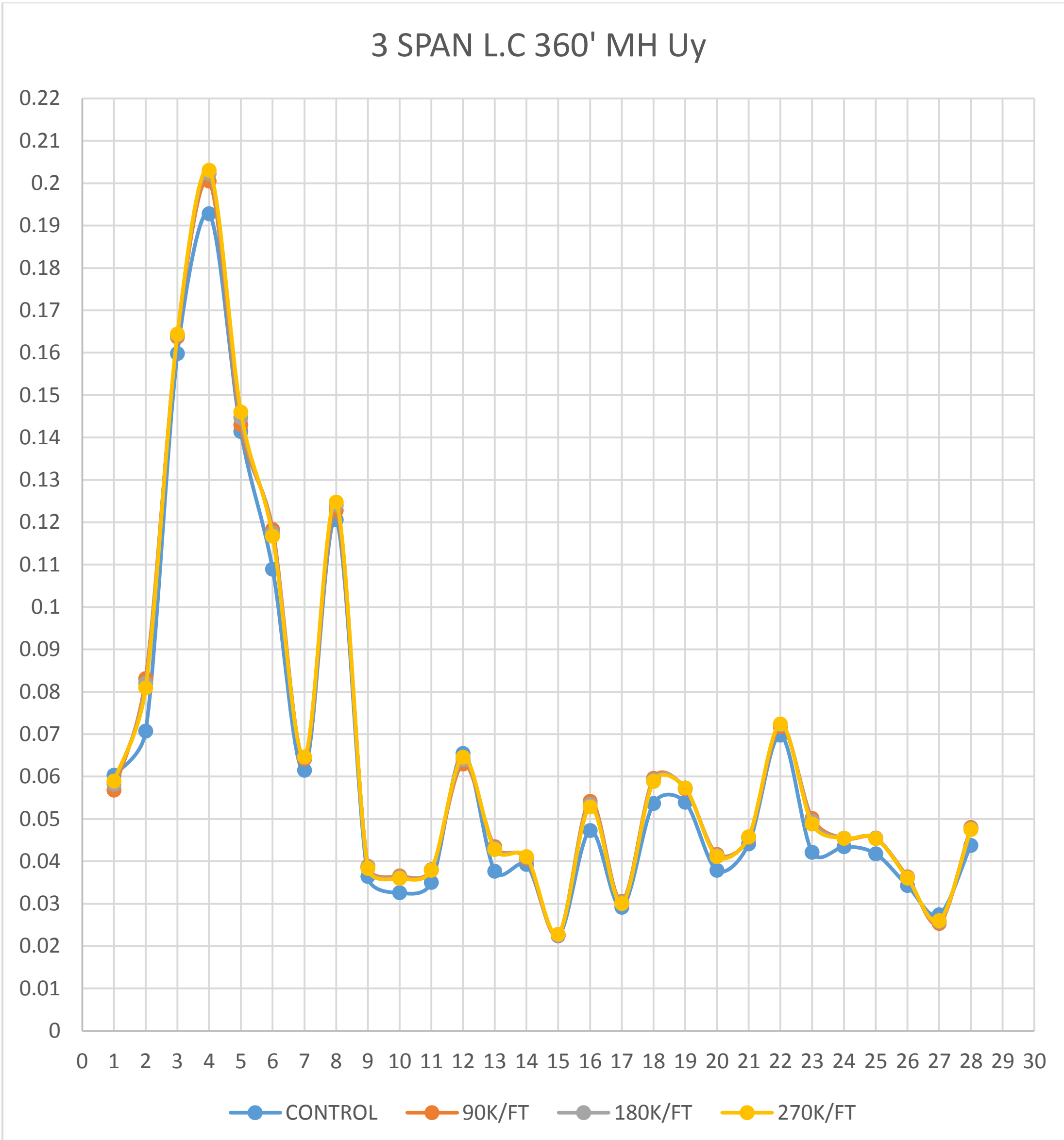


Fig. 3-56 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

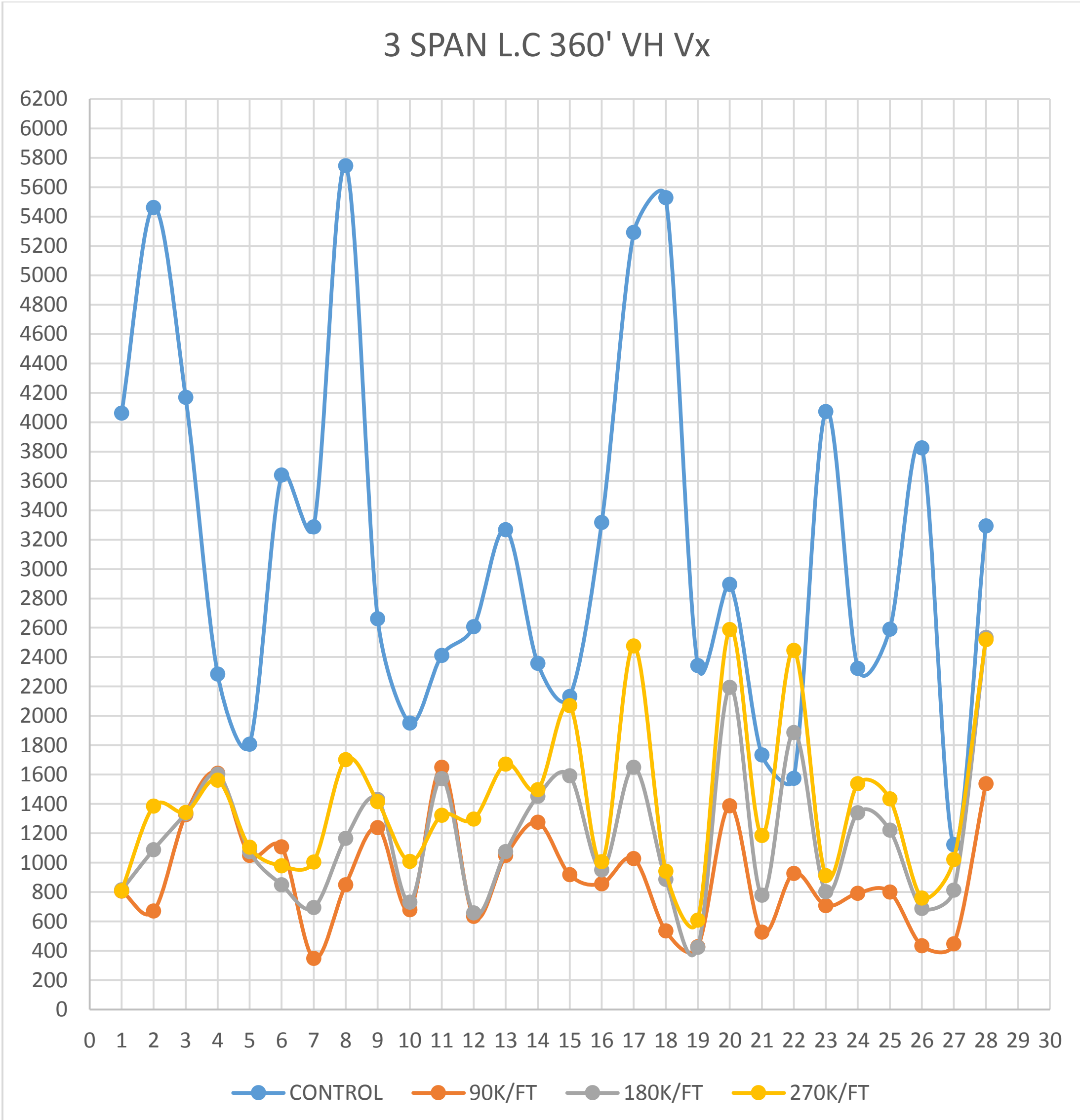


Fig. 3-57 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

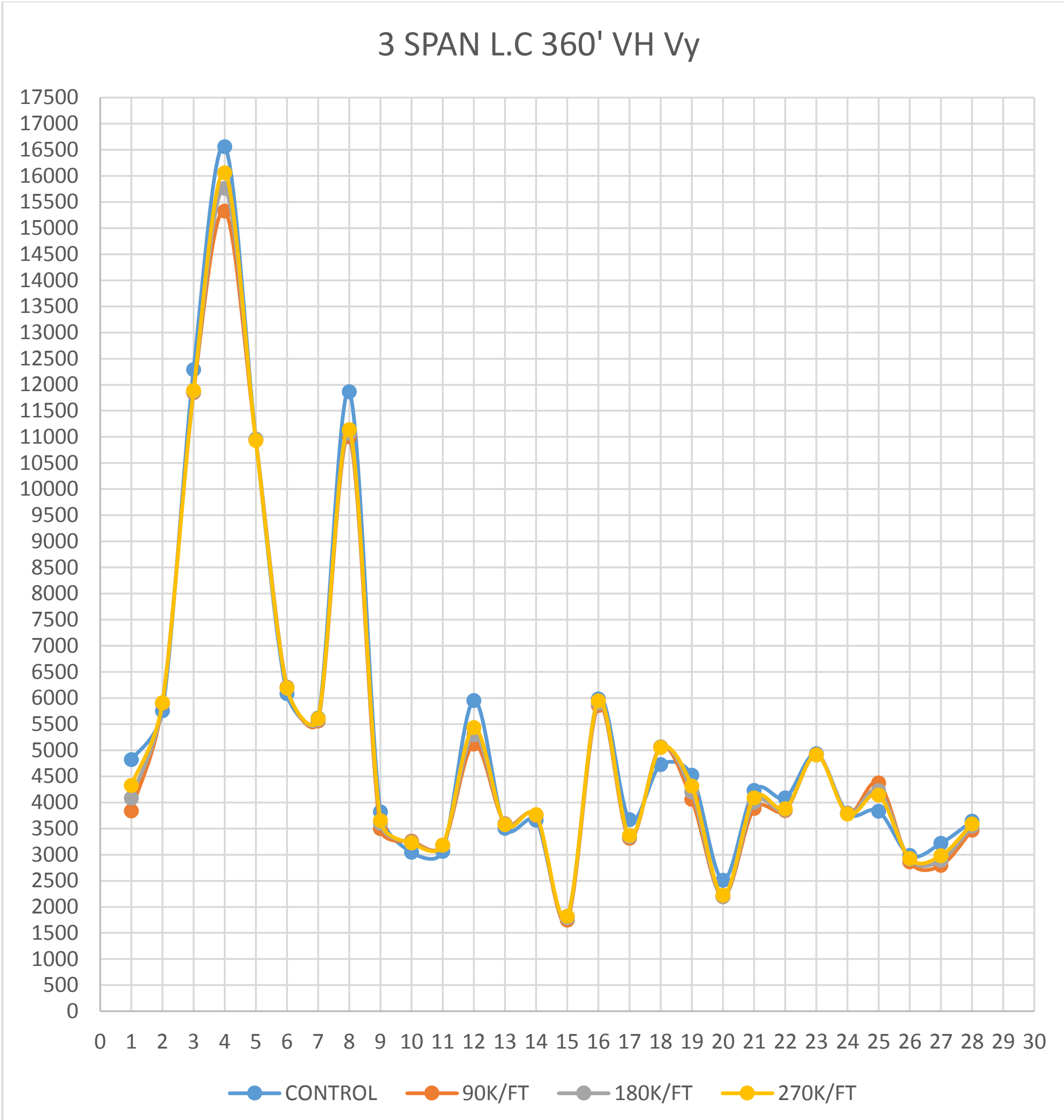


Fig. 3-58 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

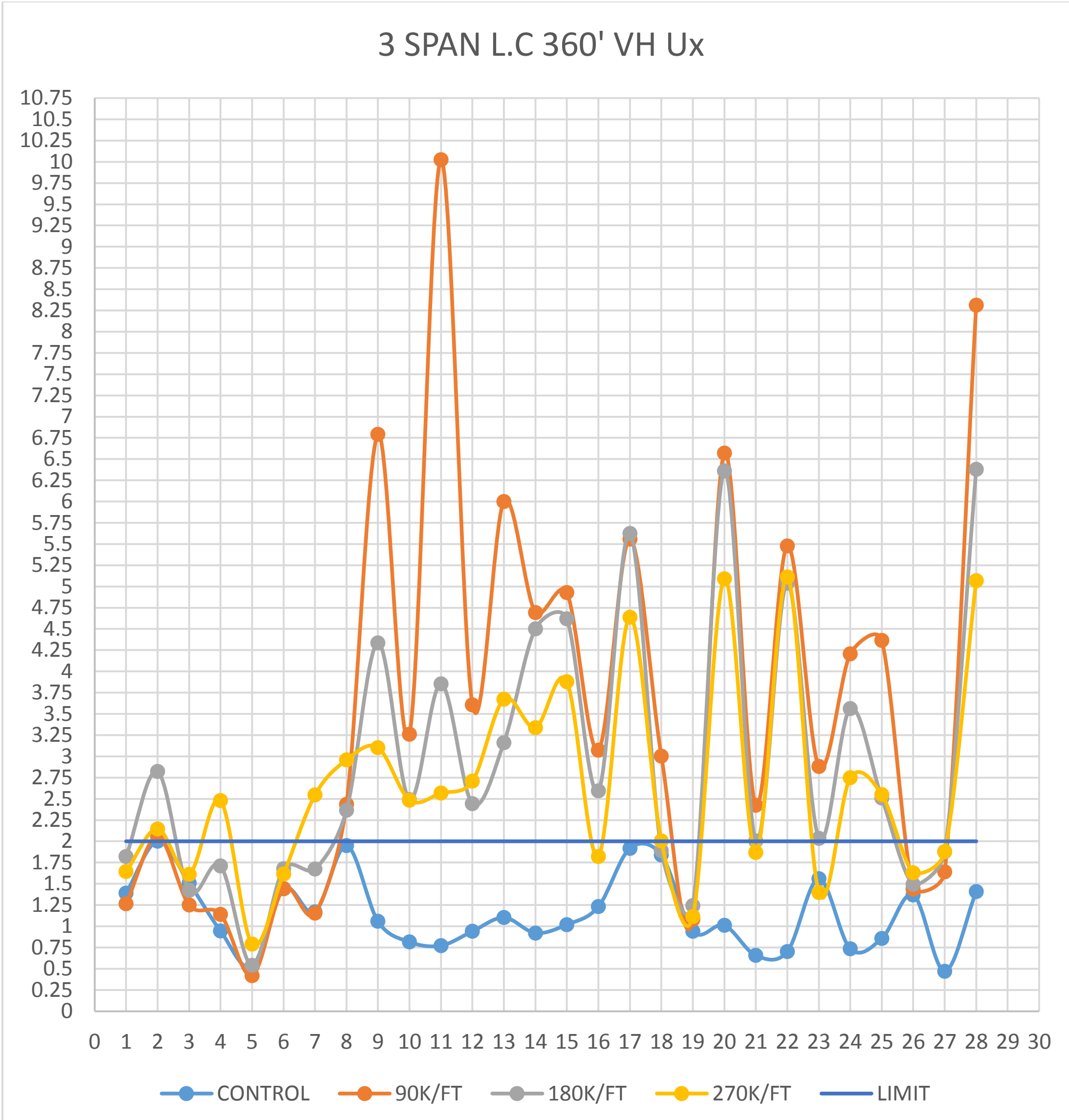


Fig. 3-59 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

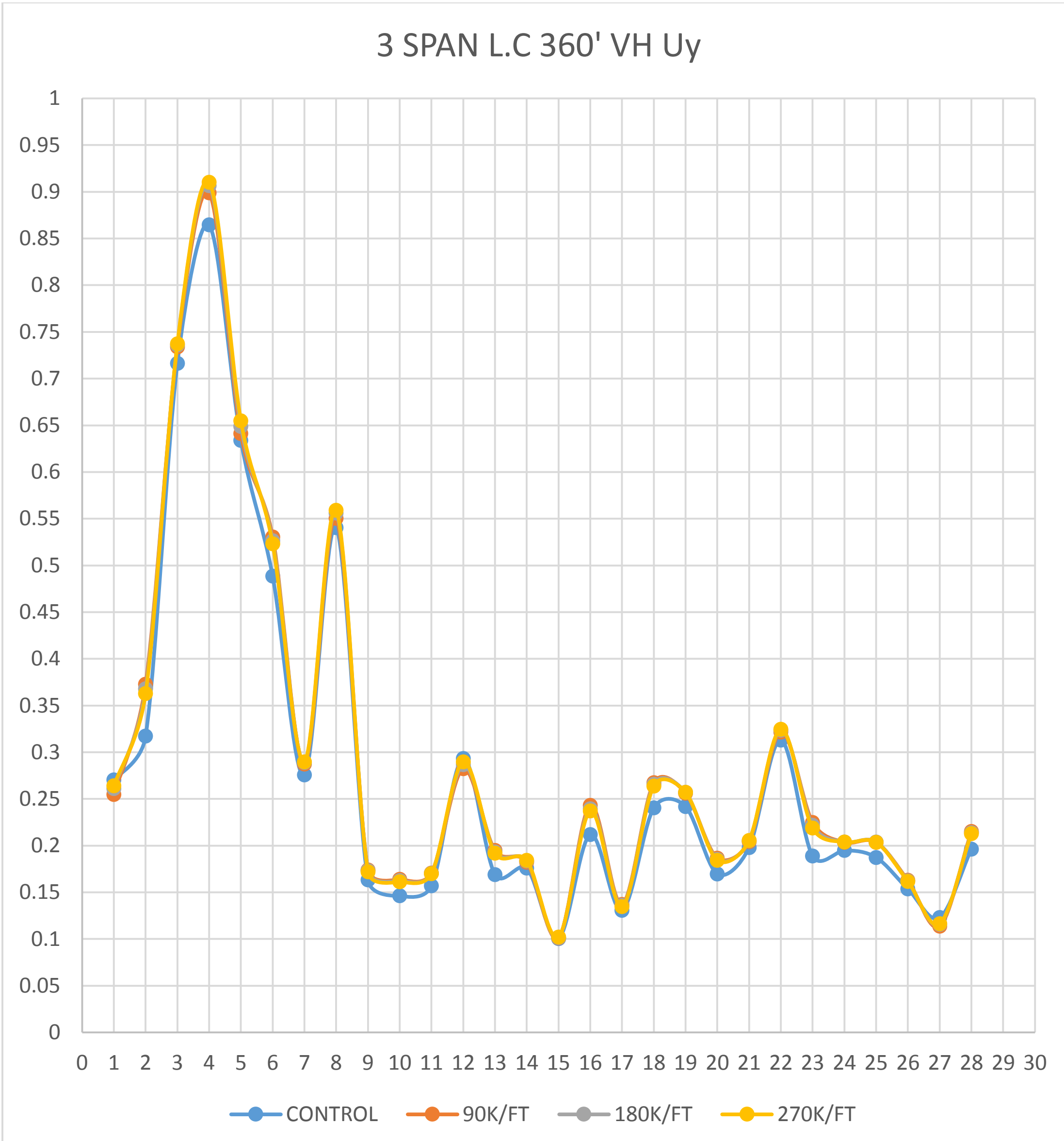


Fig. 3-60 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that all three stiffnesses can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 5746.171

90 K/Ft = 1651.113

180 K/Ft = 2534.207

270 K/Ft = 2588.979

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

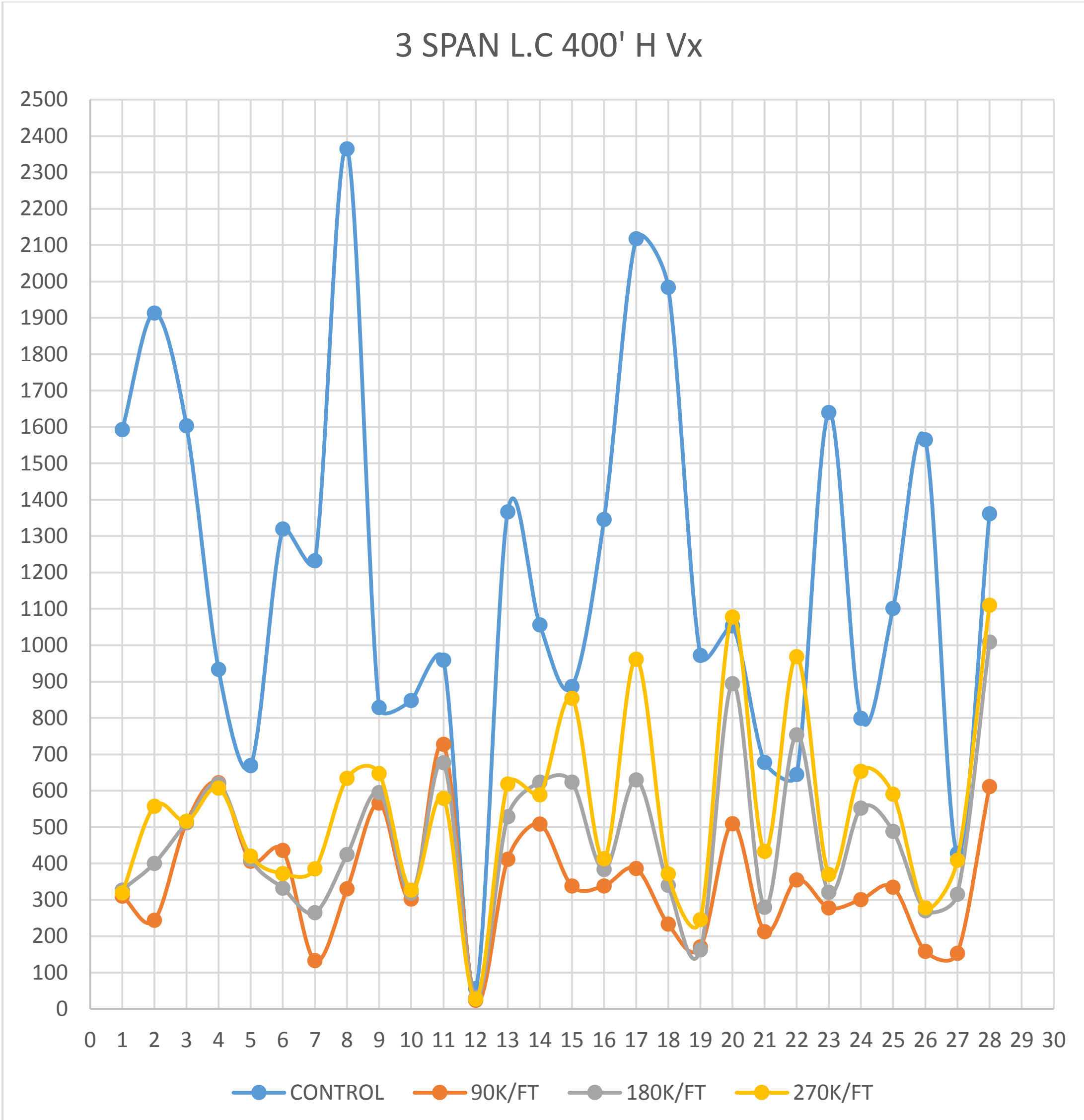


Fig. 3-61 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

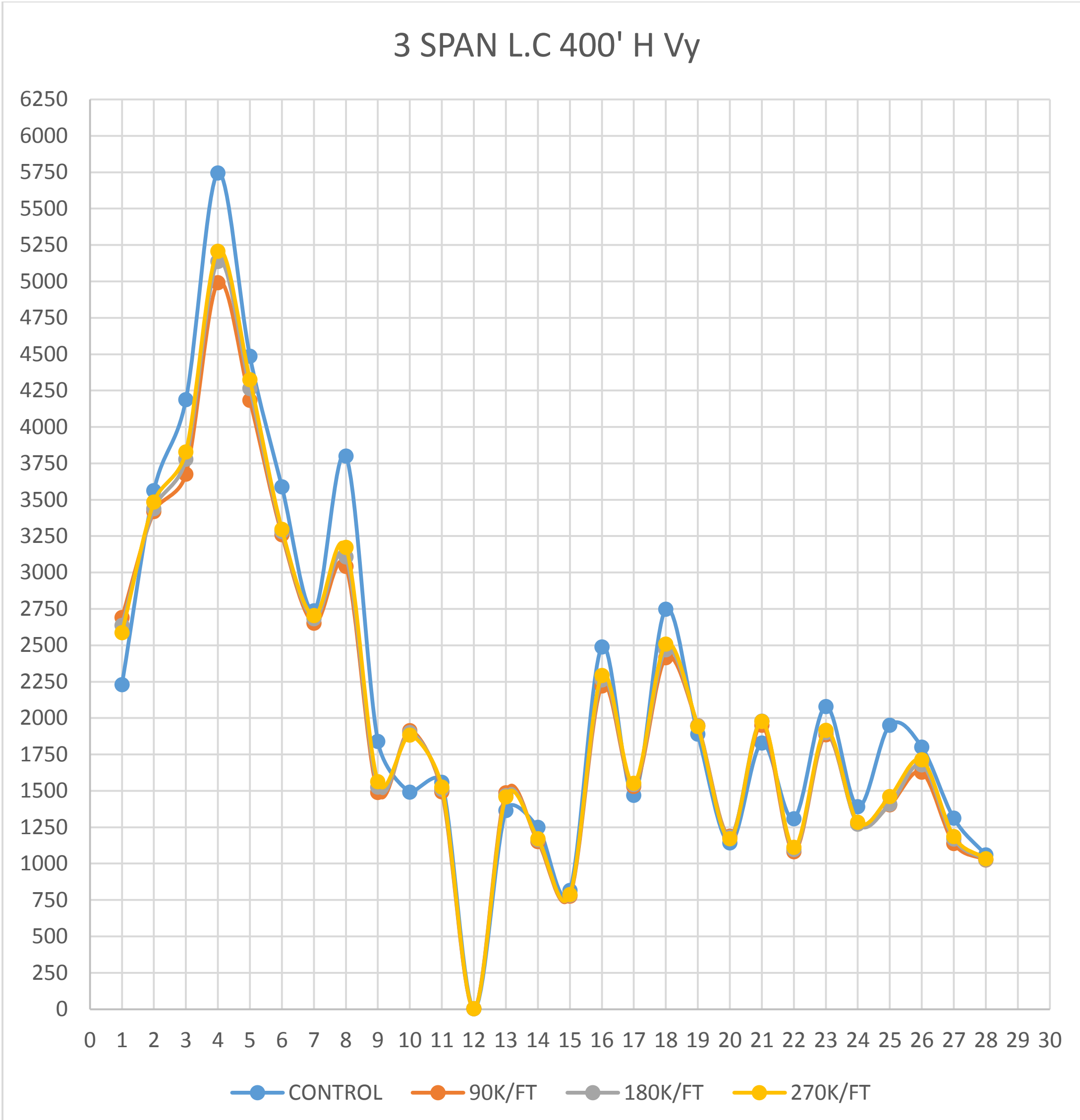


Fig. 3-62 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

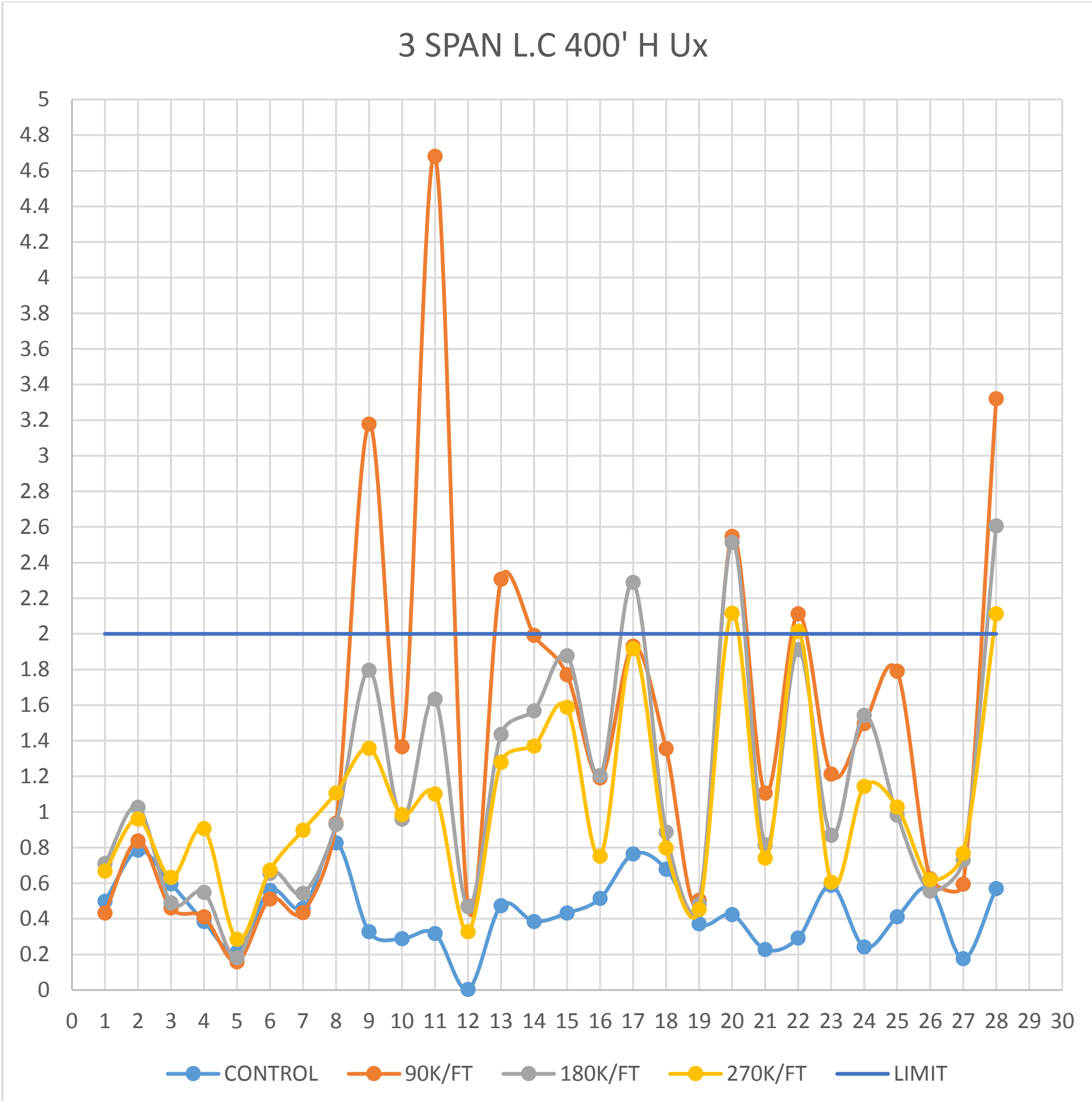


Fig. 3-63 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

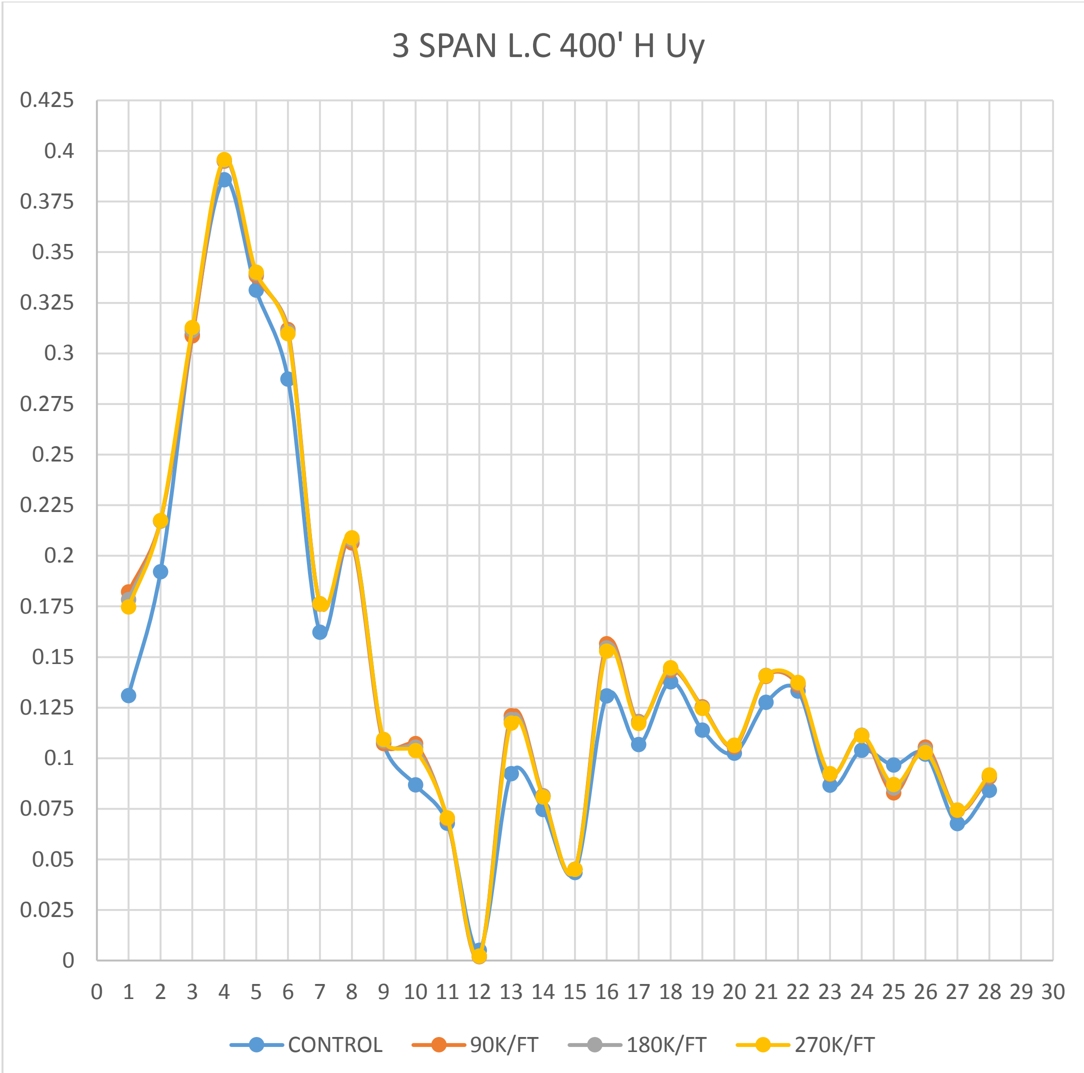


Fig. 3-64 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the three span bridge.

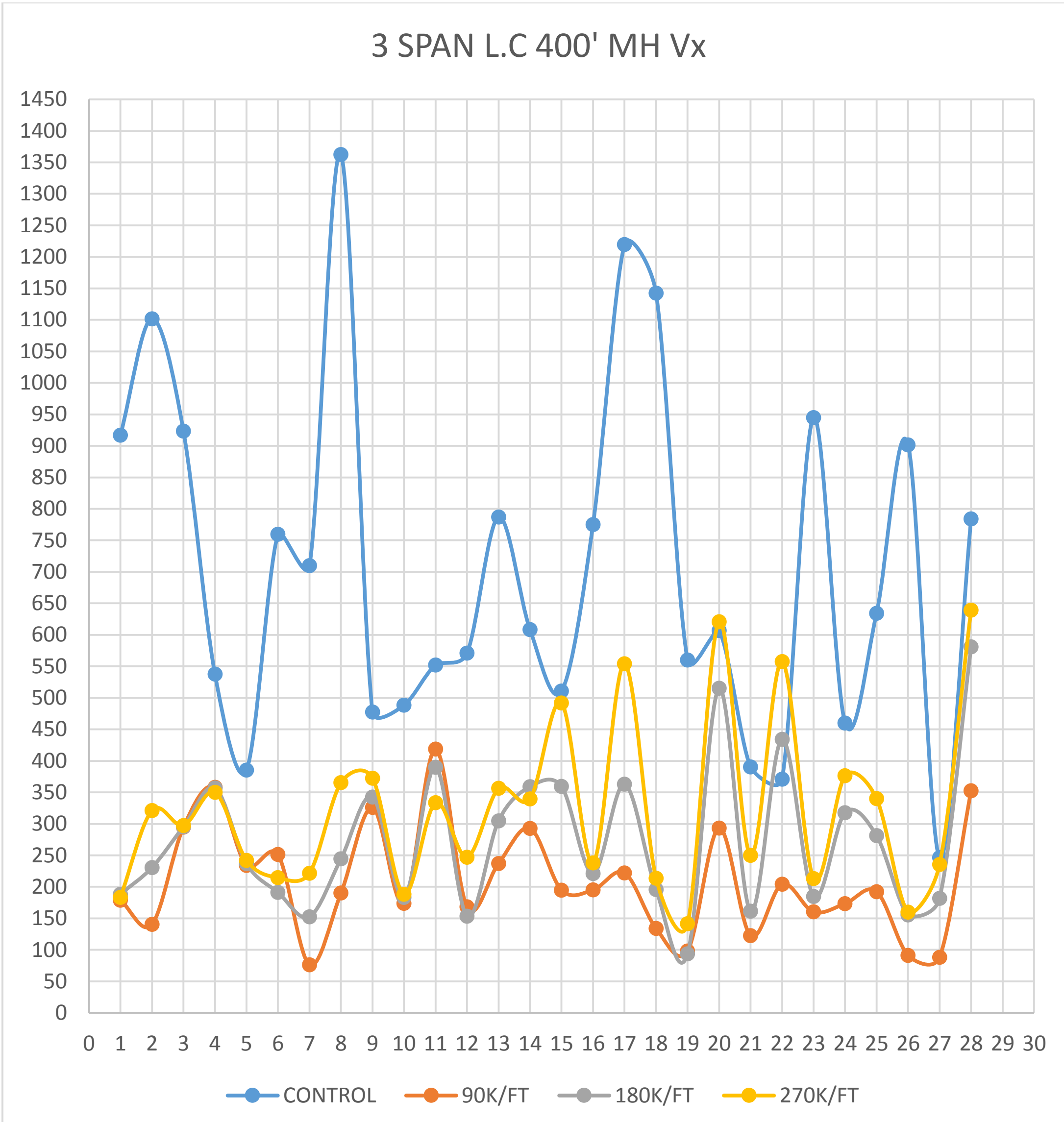


Fig. 3-65 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

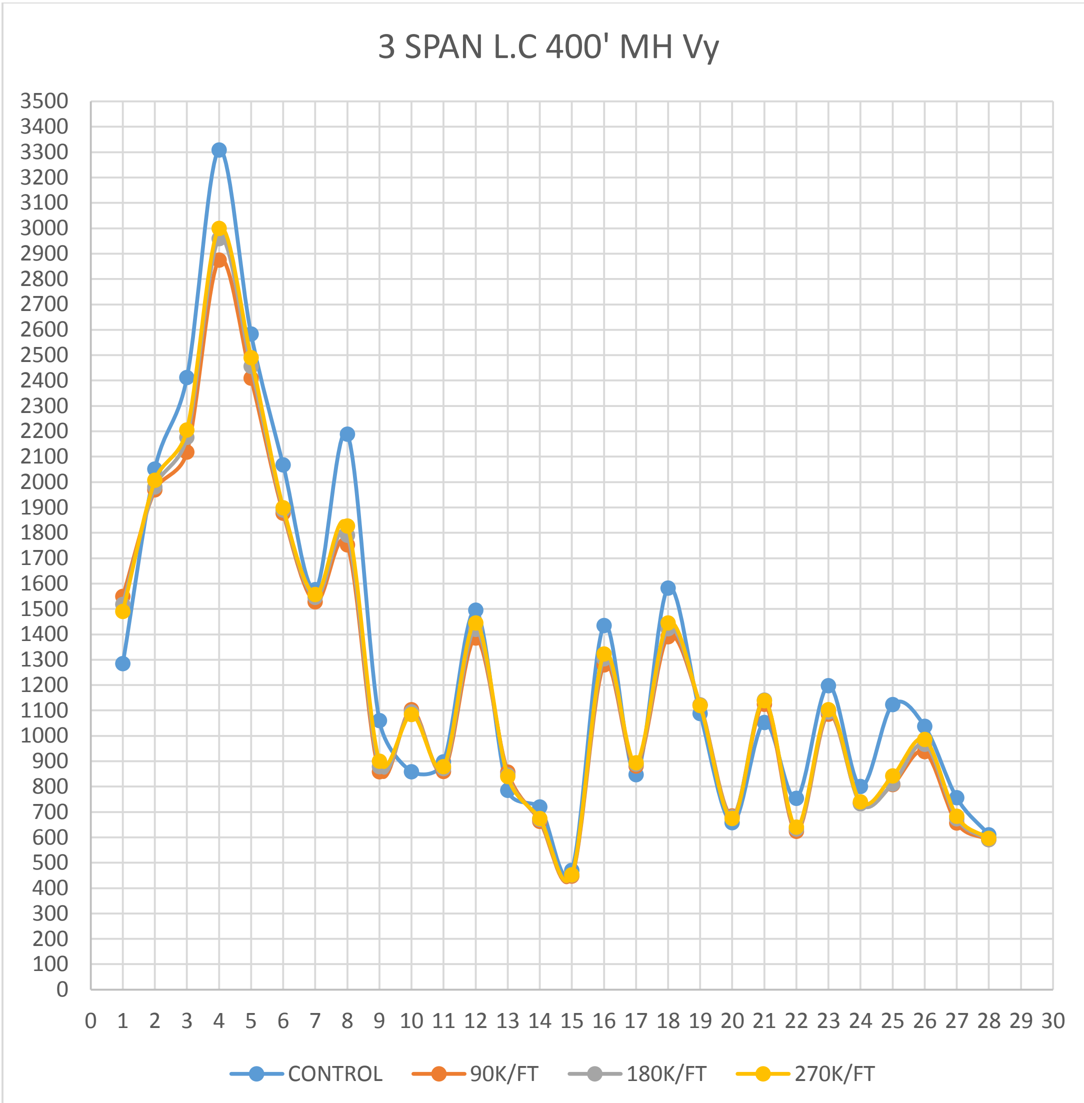


Fig. 3-66 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

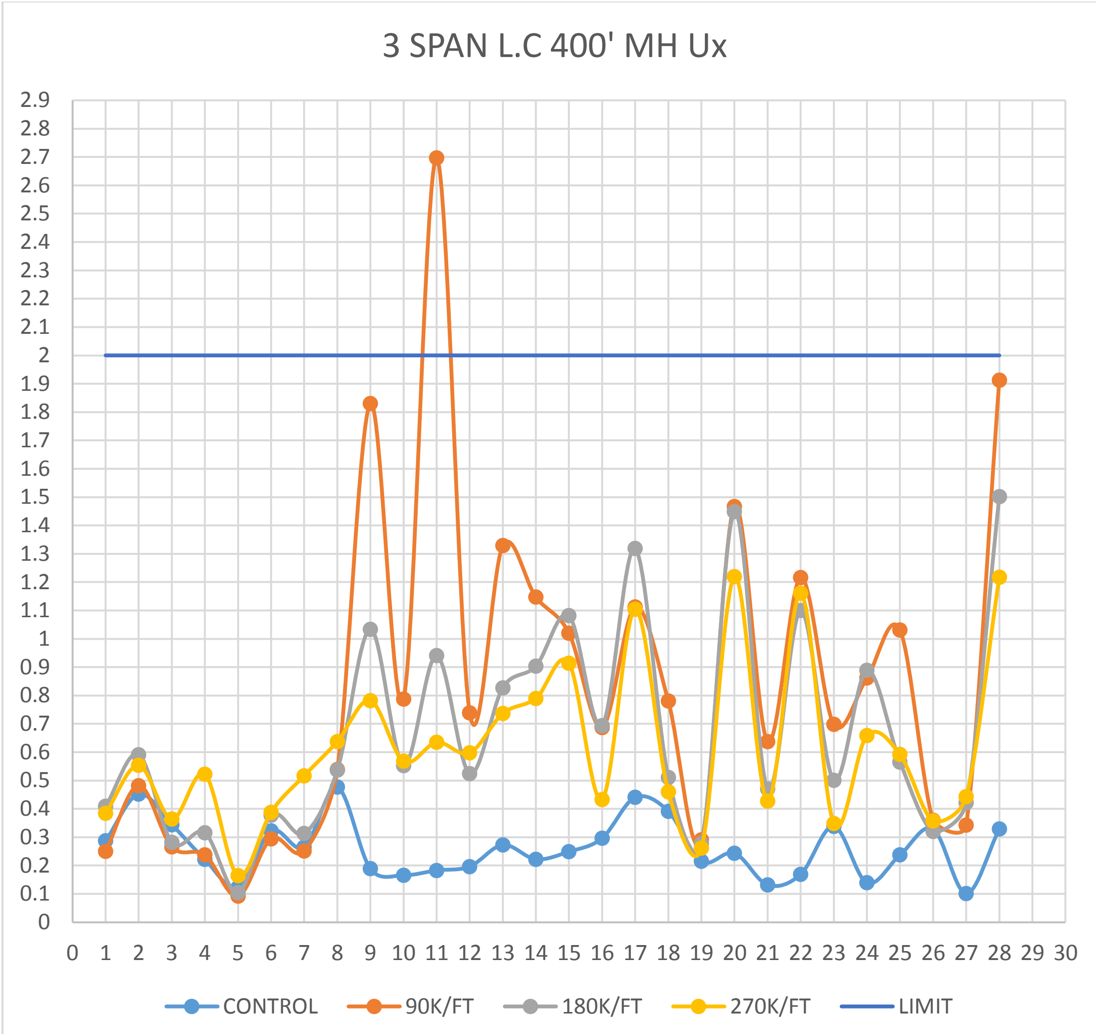


Fig. 3-67 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

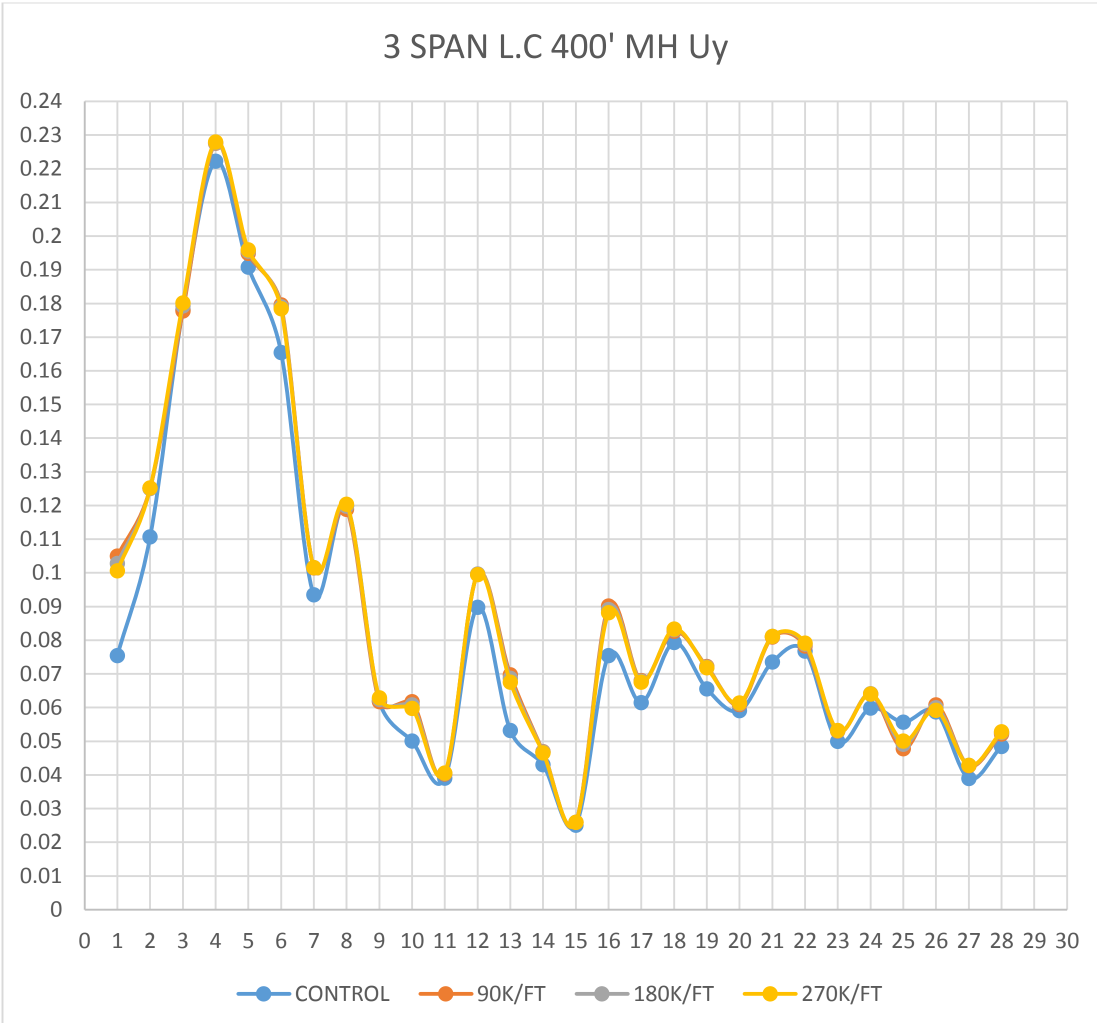


Fig. 3-68 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the three span bridge.

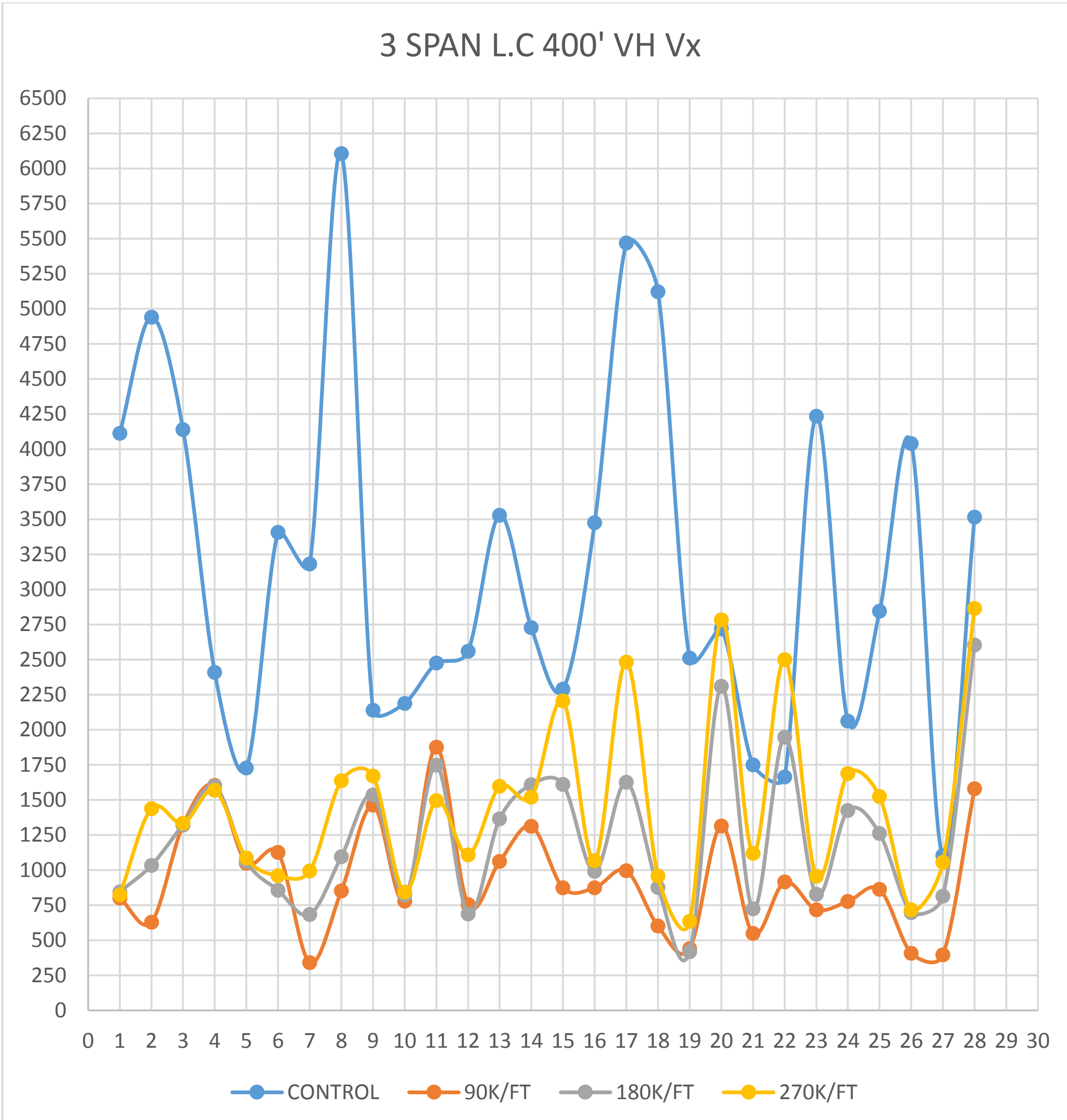


Fig. 3-69 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

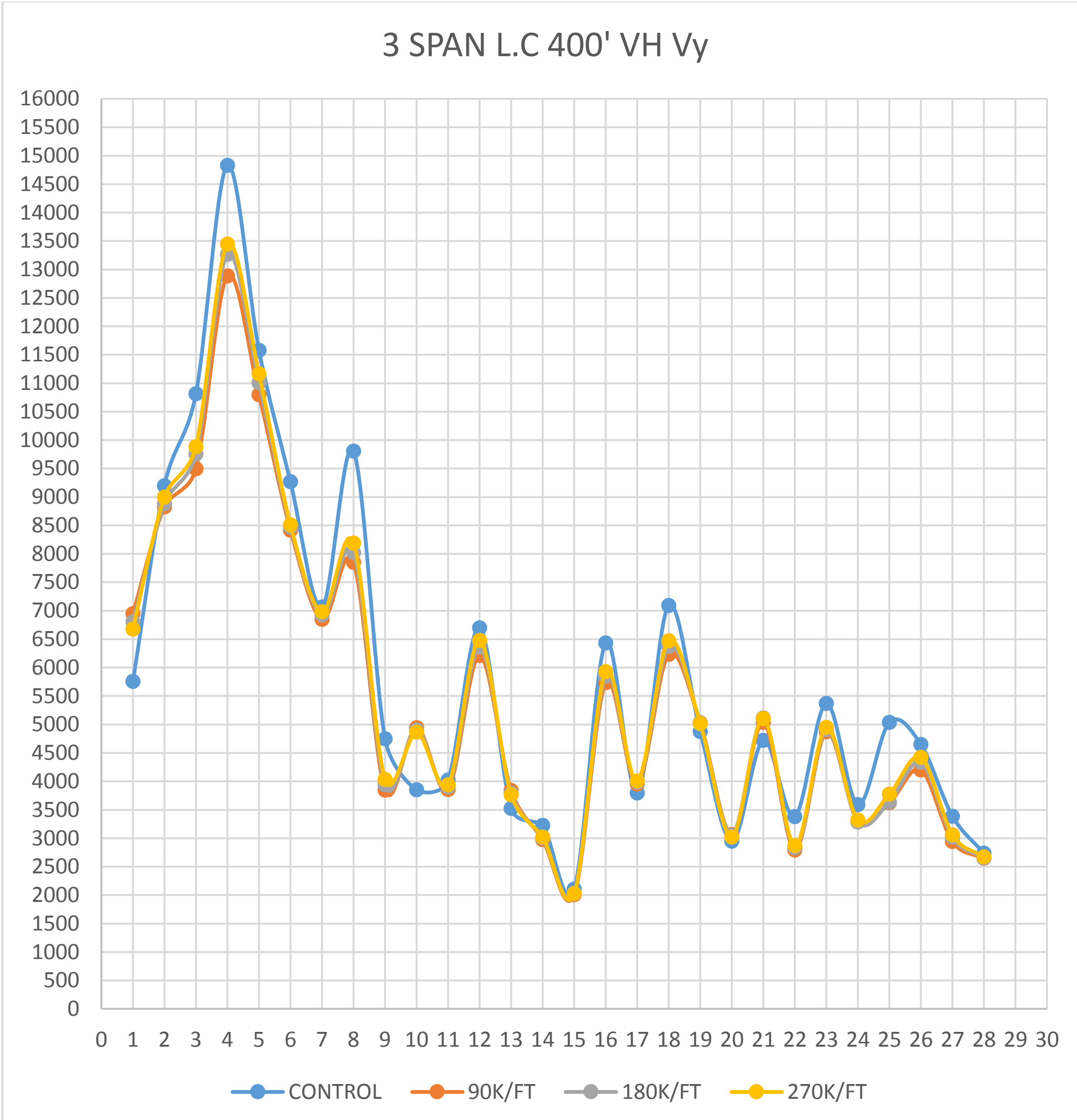


Fig. 3-70 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

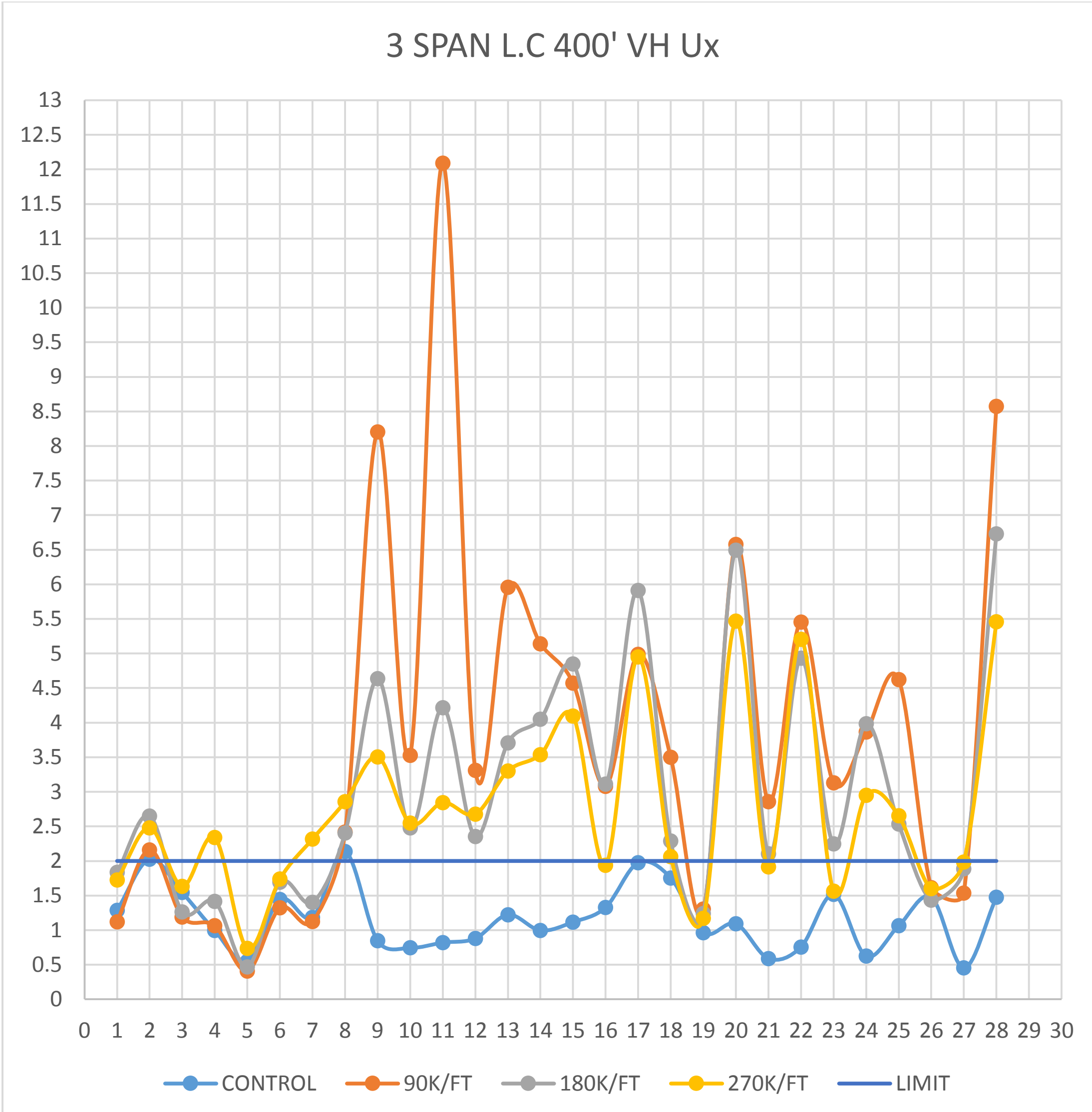


Fig. 3-71 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

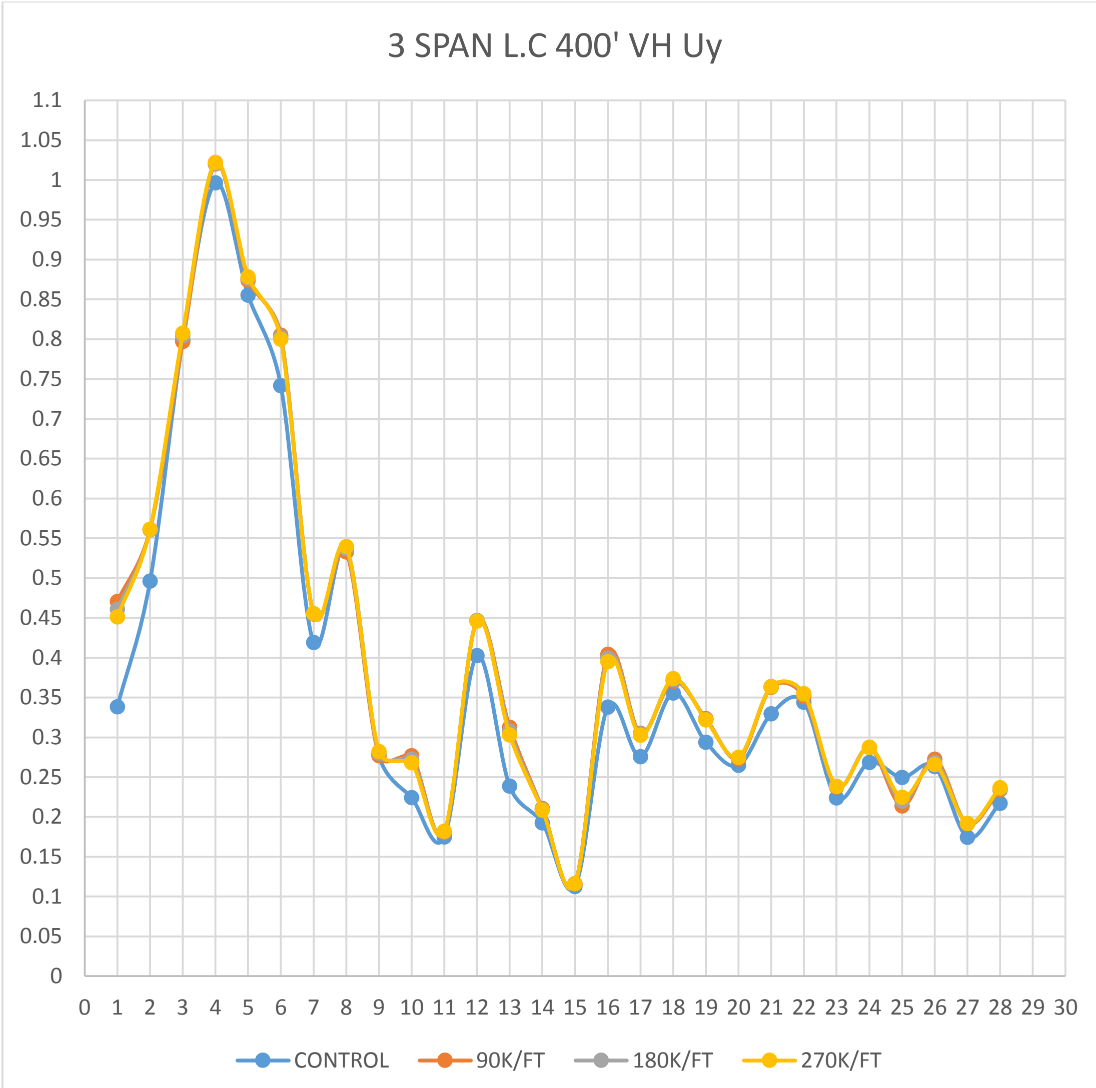


Fig. 3-72 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that all three stiffnesses can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 6106.276

90 K/Ft = 1877.702

180 K/Ft = 2603.859

270 K/Ft = 2866.197

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

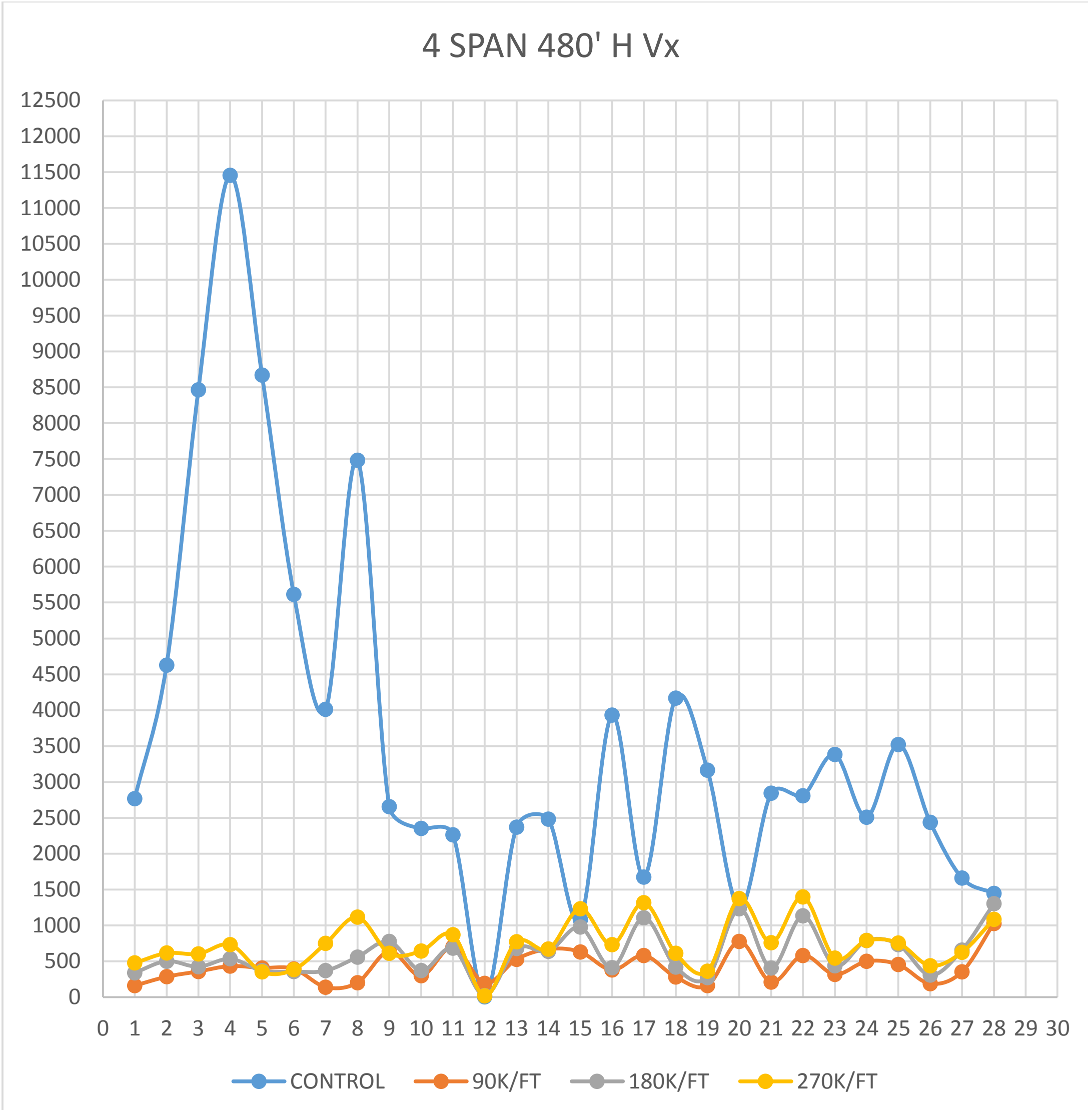


Fig. 3-73 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

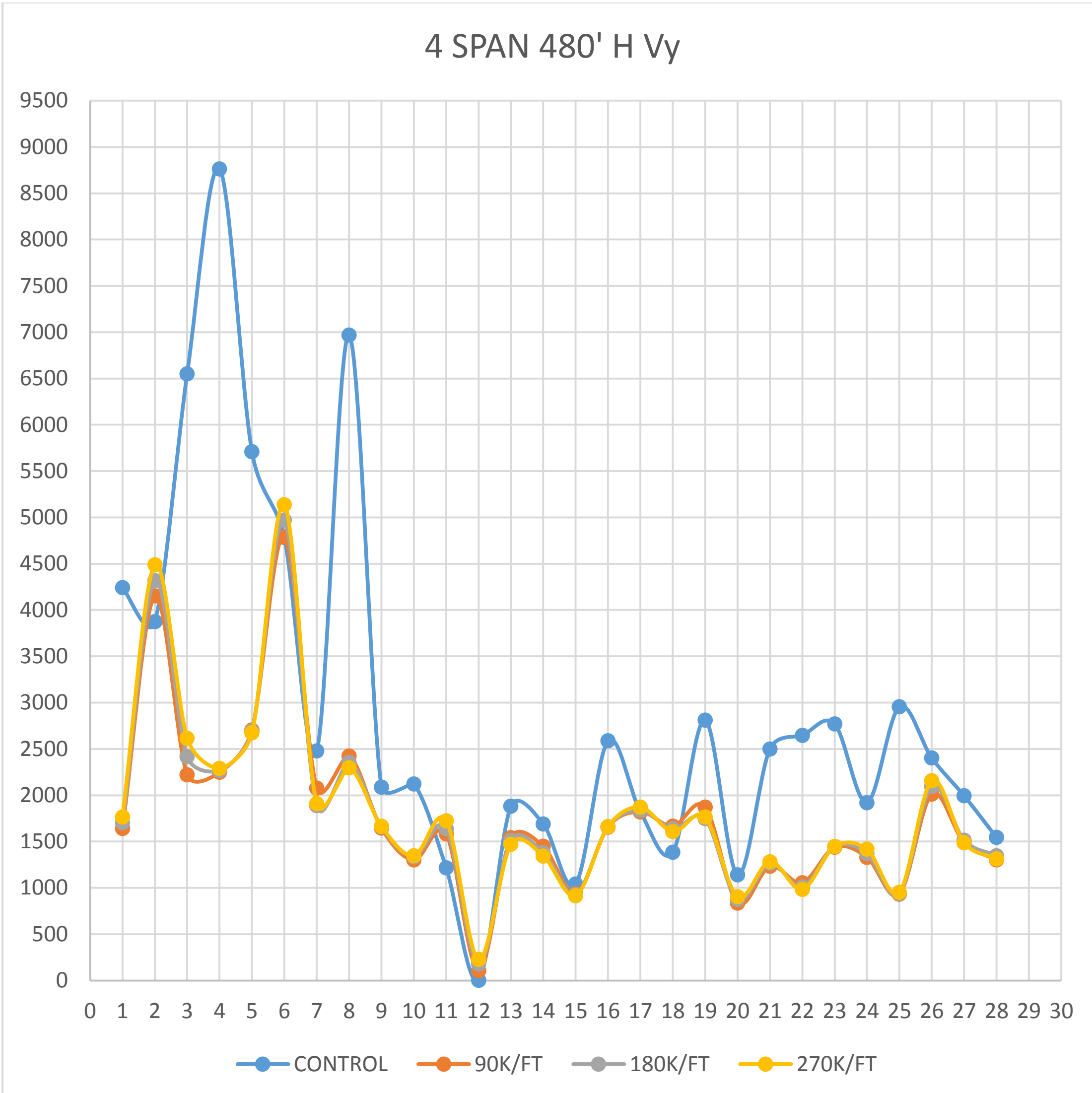


Fig. 3-74 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

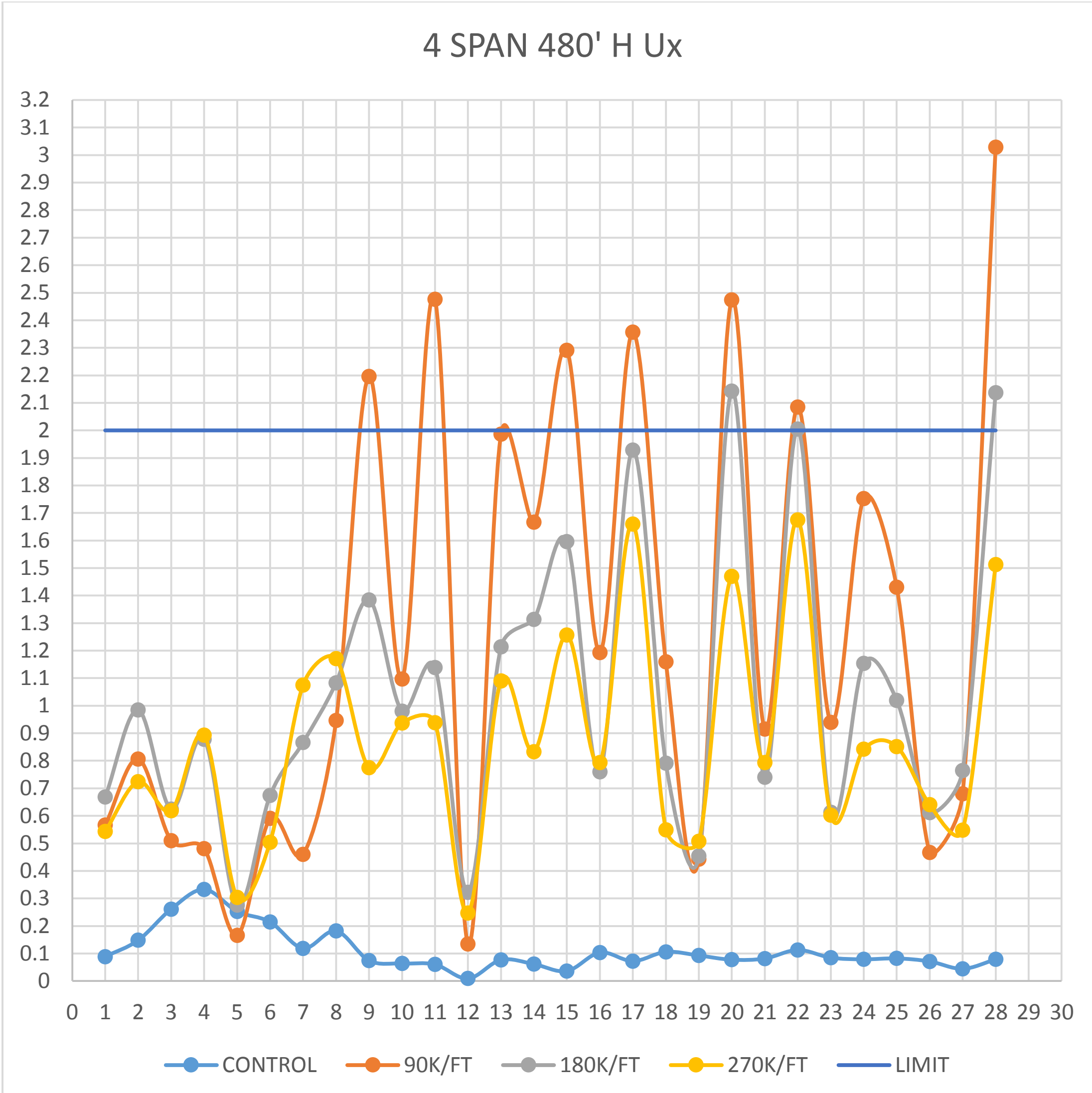


Fig. 3-75 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

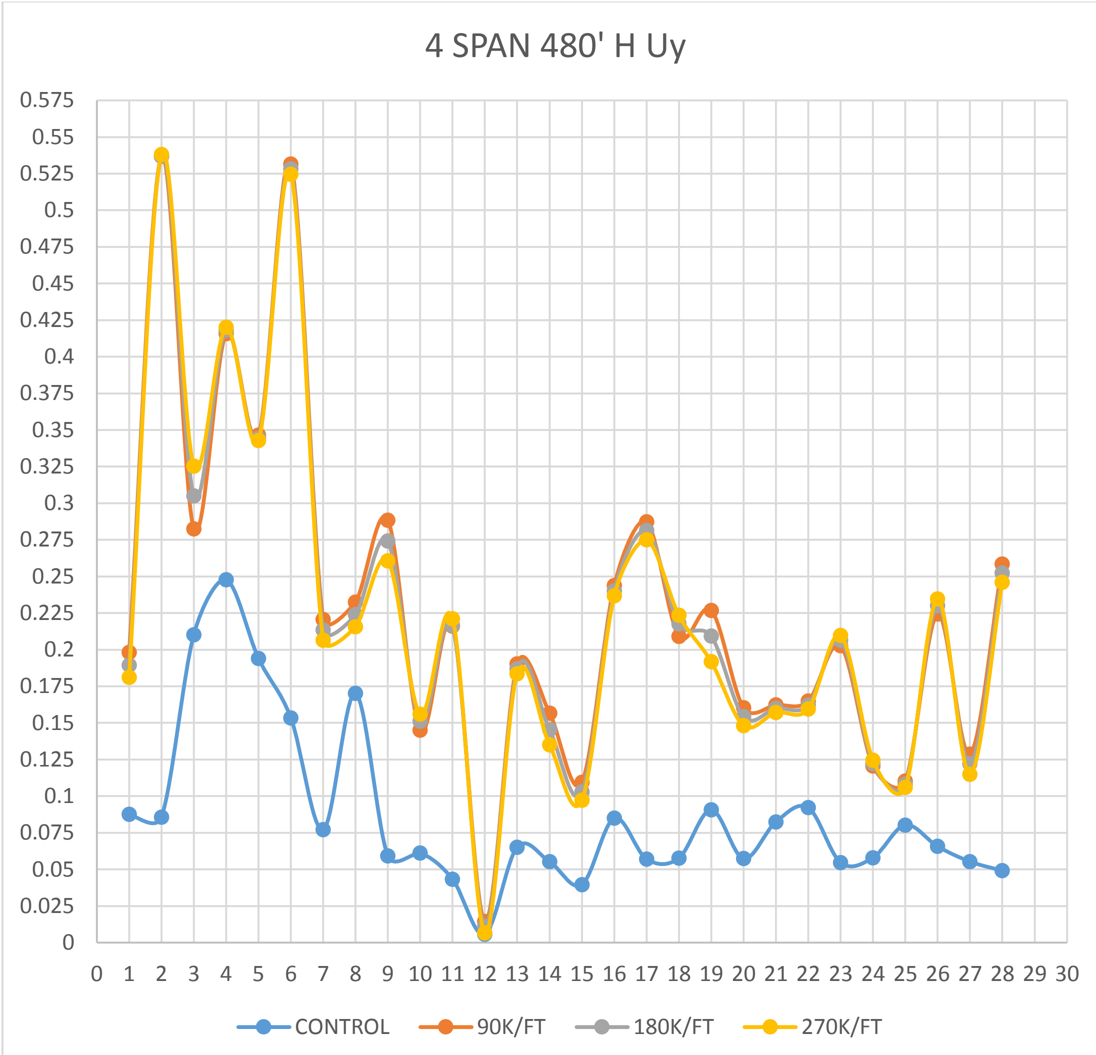


Fig. 3-76 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

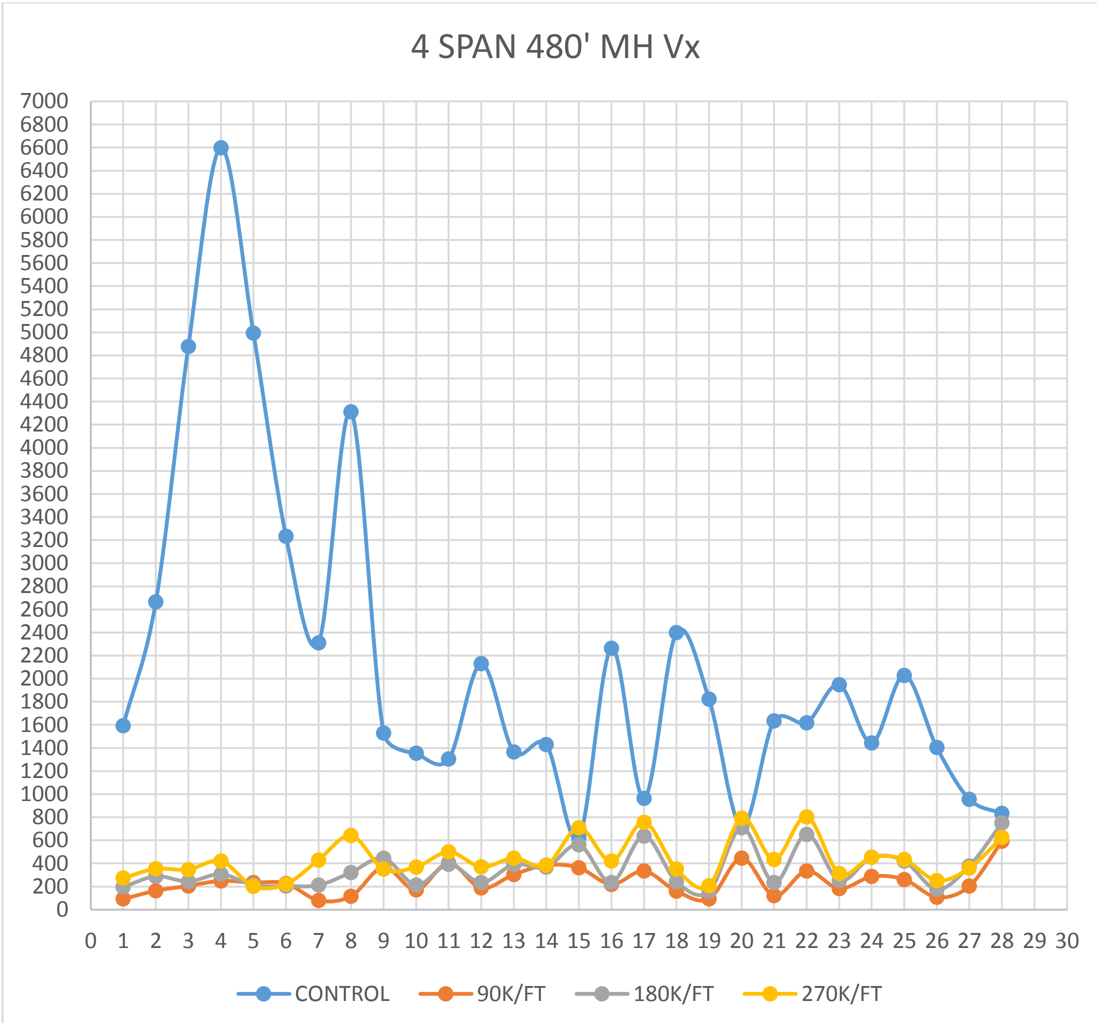


Fig. 3-77 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

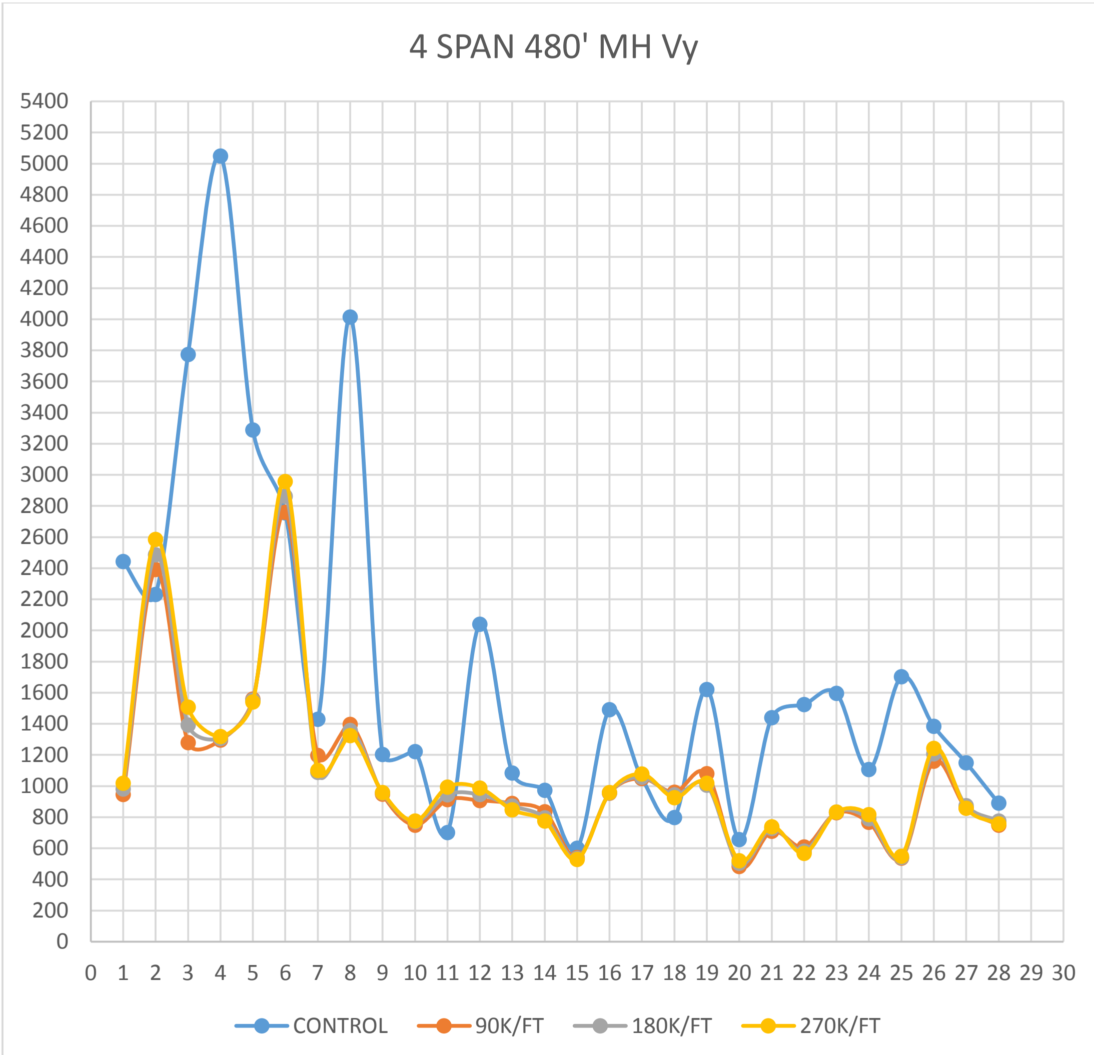


Fig. 3-78 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

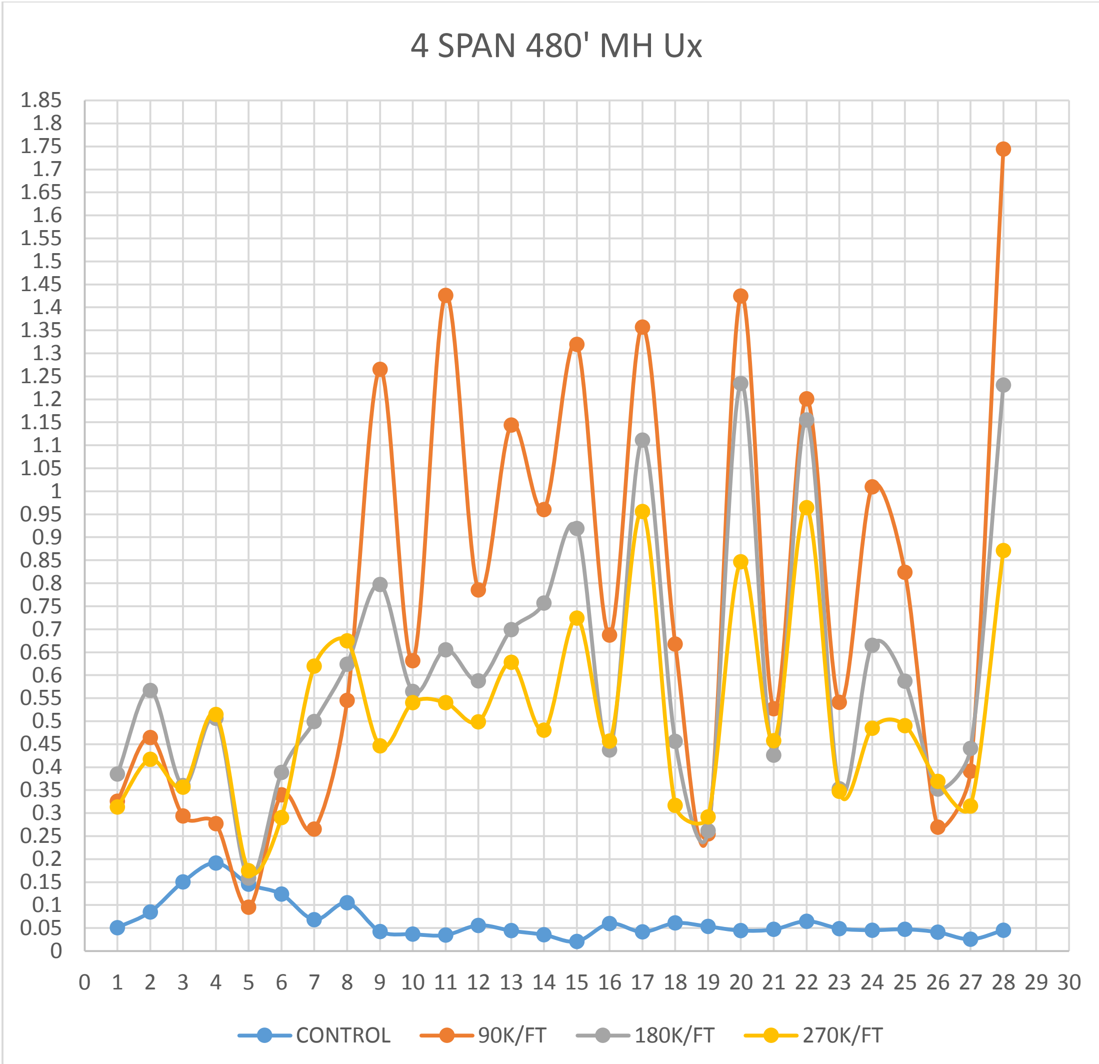


Fig. 3-79 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

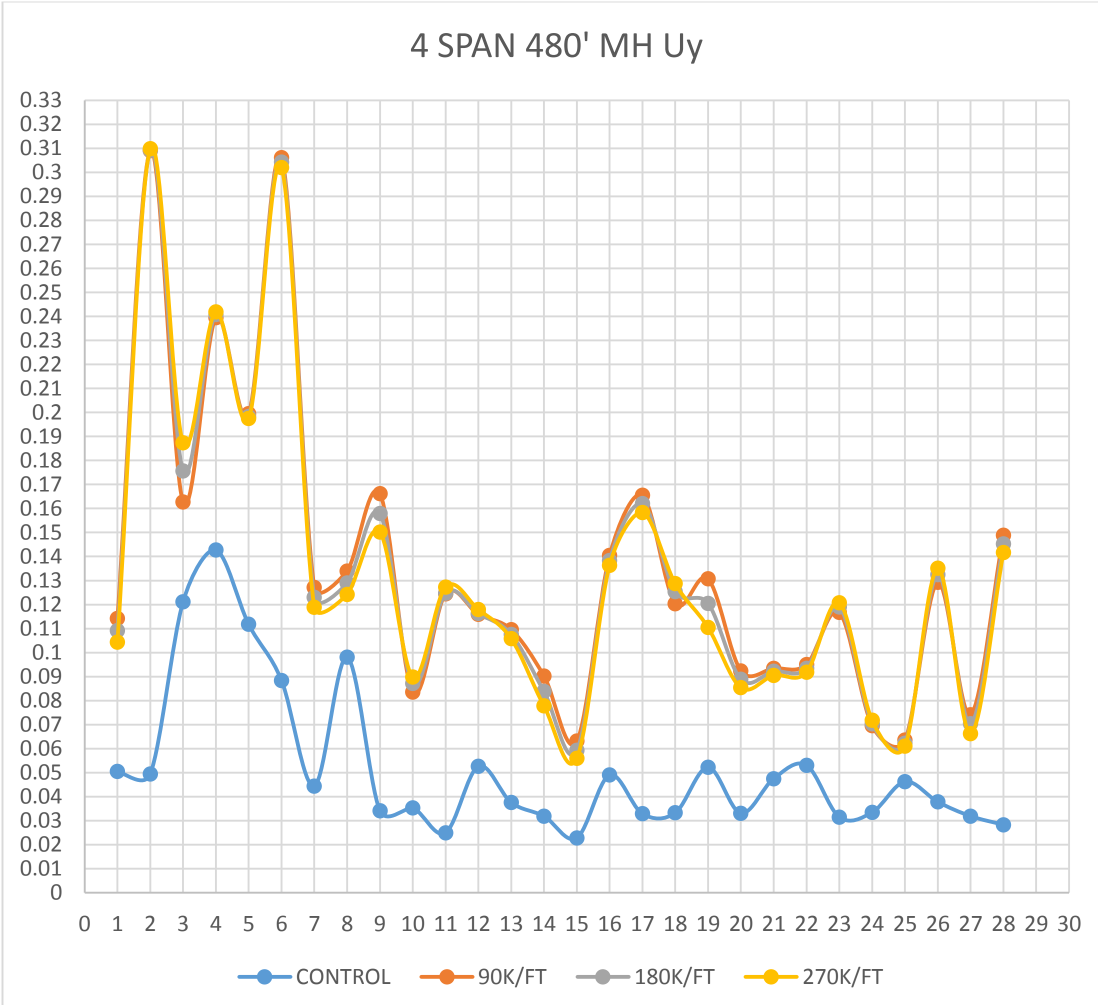


Fig. 3-80 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

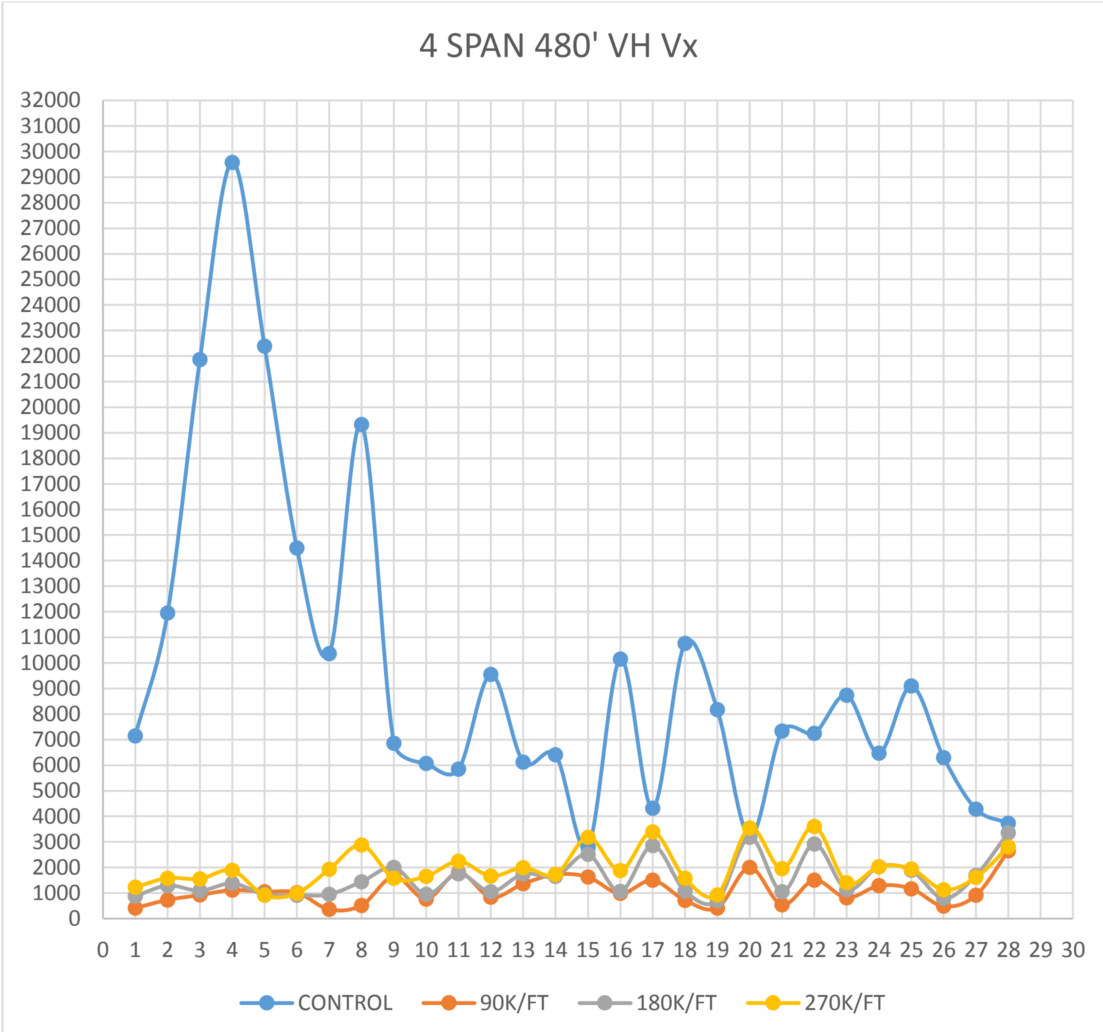


Fig. 3-81 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

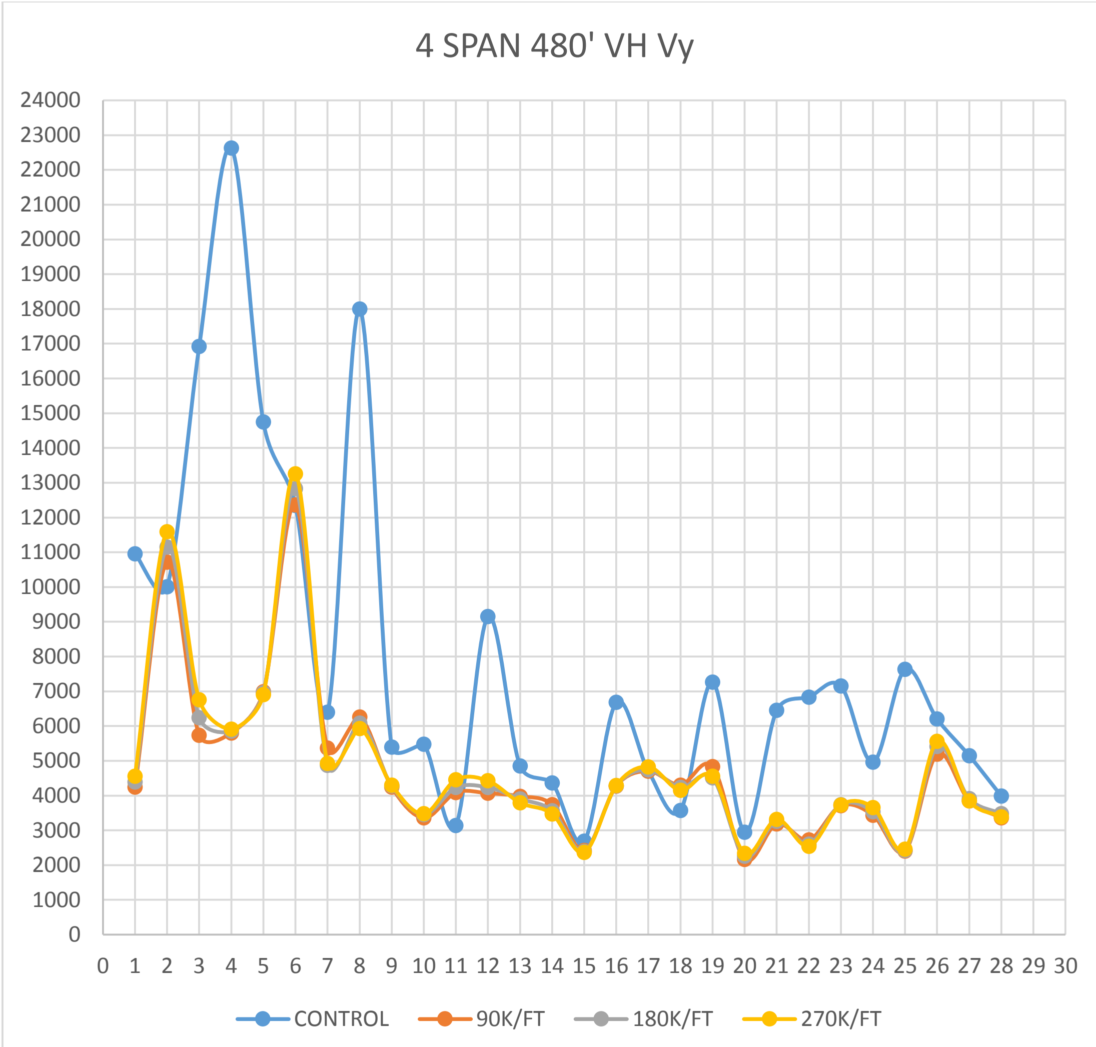


Fig. 3-82 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

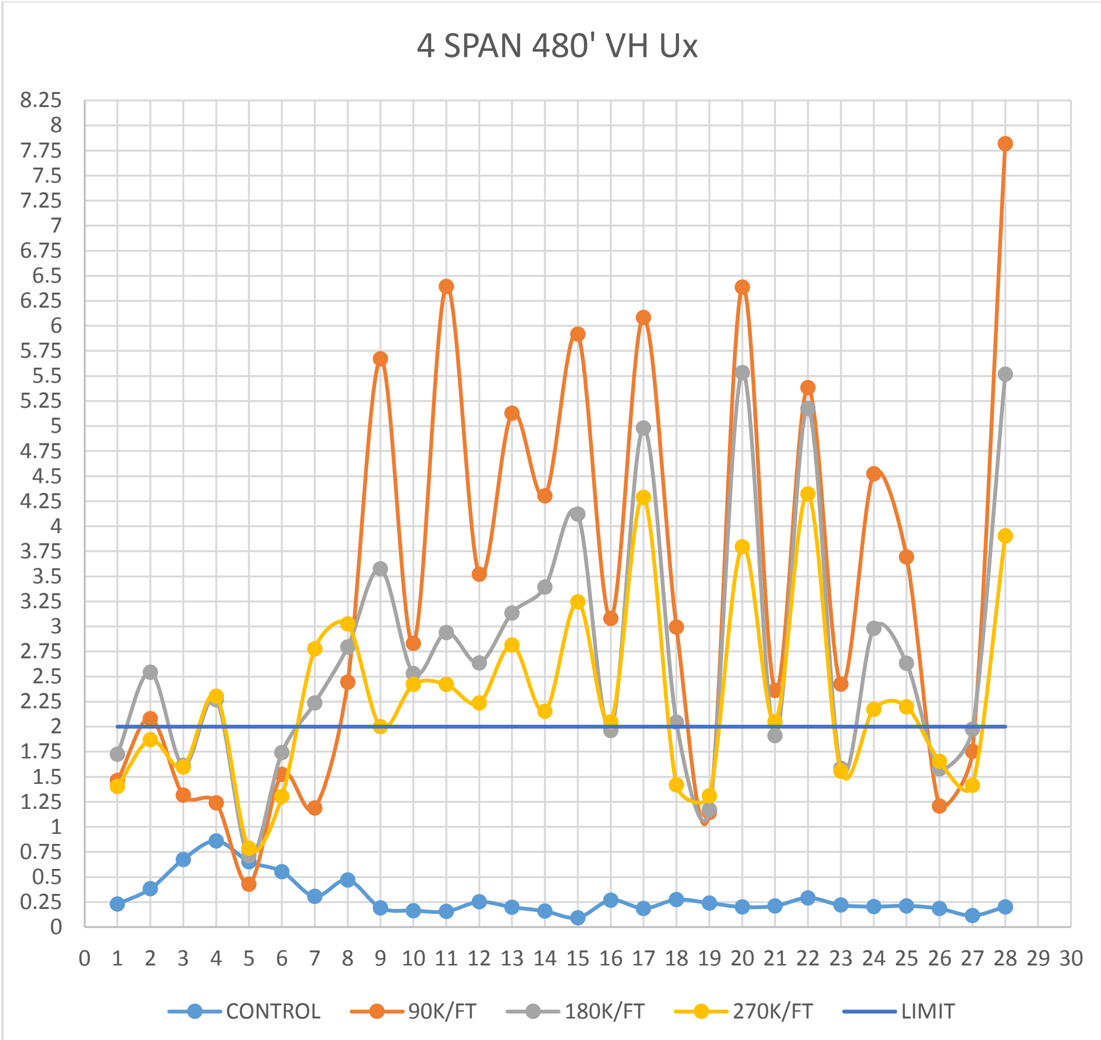


Fig. 3-83 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

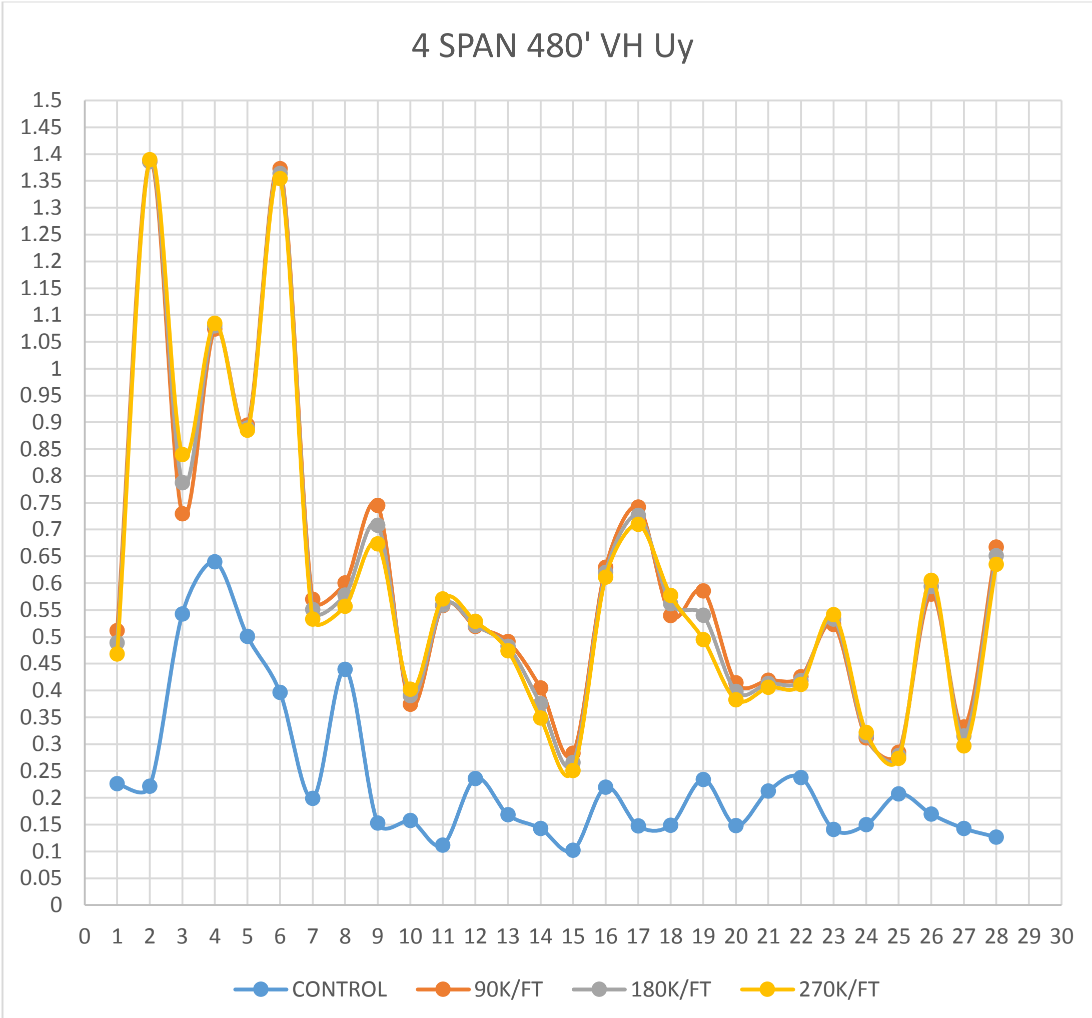


Fig. 3-84 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that all three stiffnesses can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 29579.35

90 K/Ft = 2652.425

180 K/Ft = 3359.941

270 K/Ft = 3603.03

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

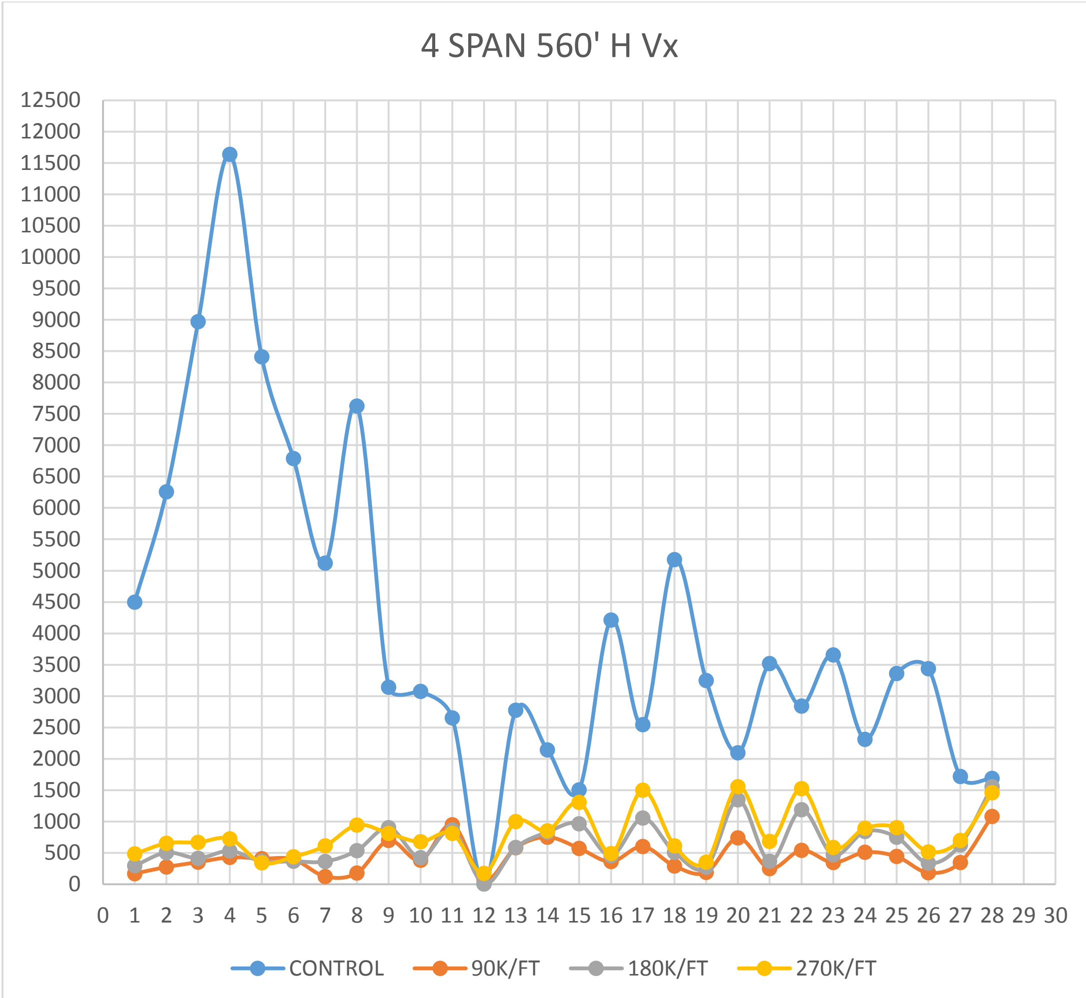


Fig. 3-85 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

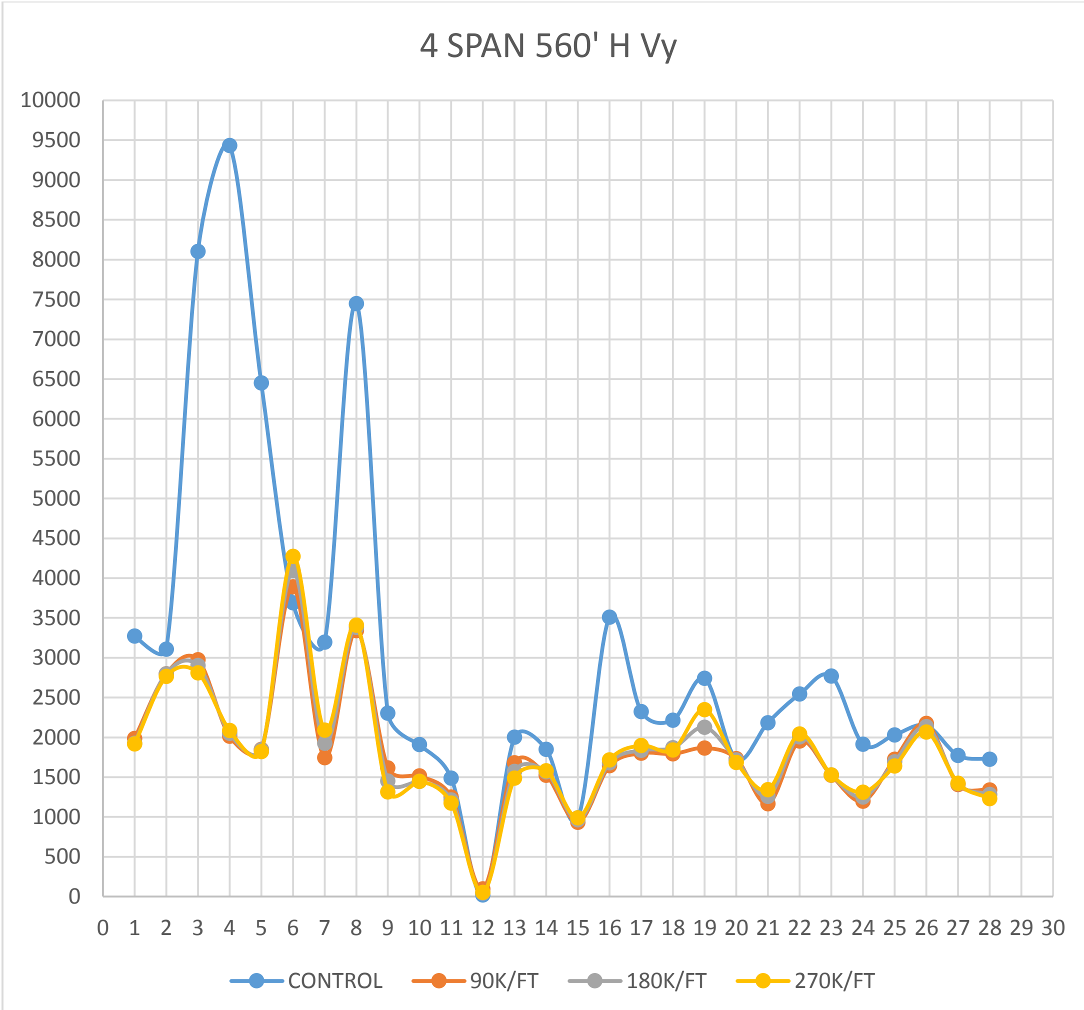


Fig. 3-86 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

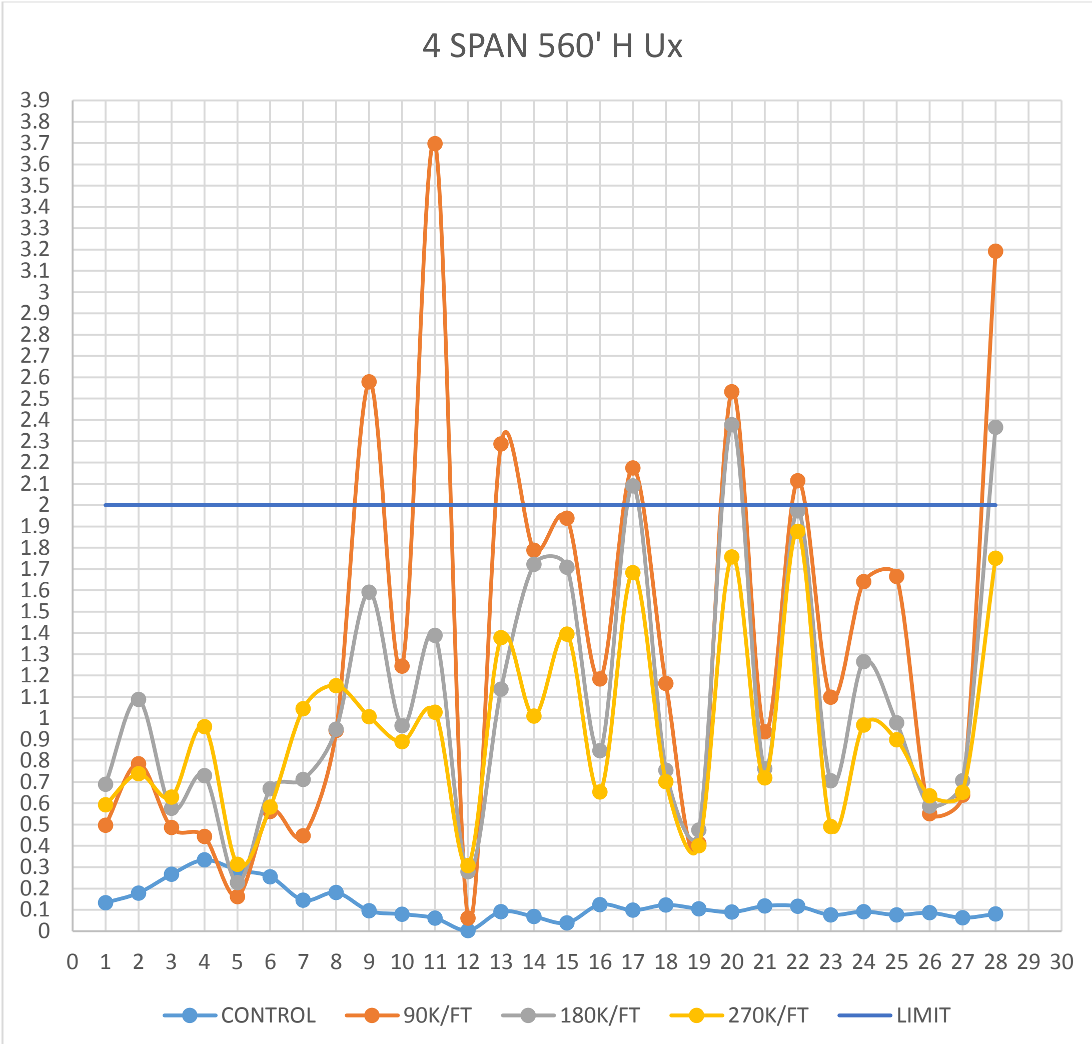


Fig. 3-87 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

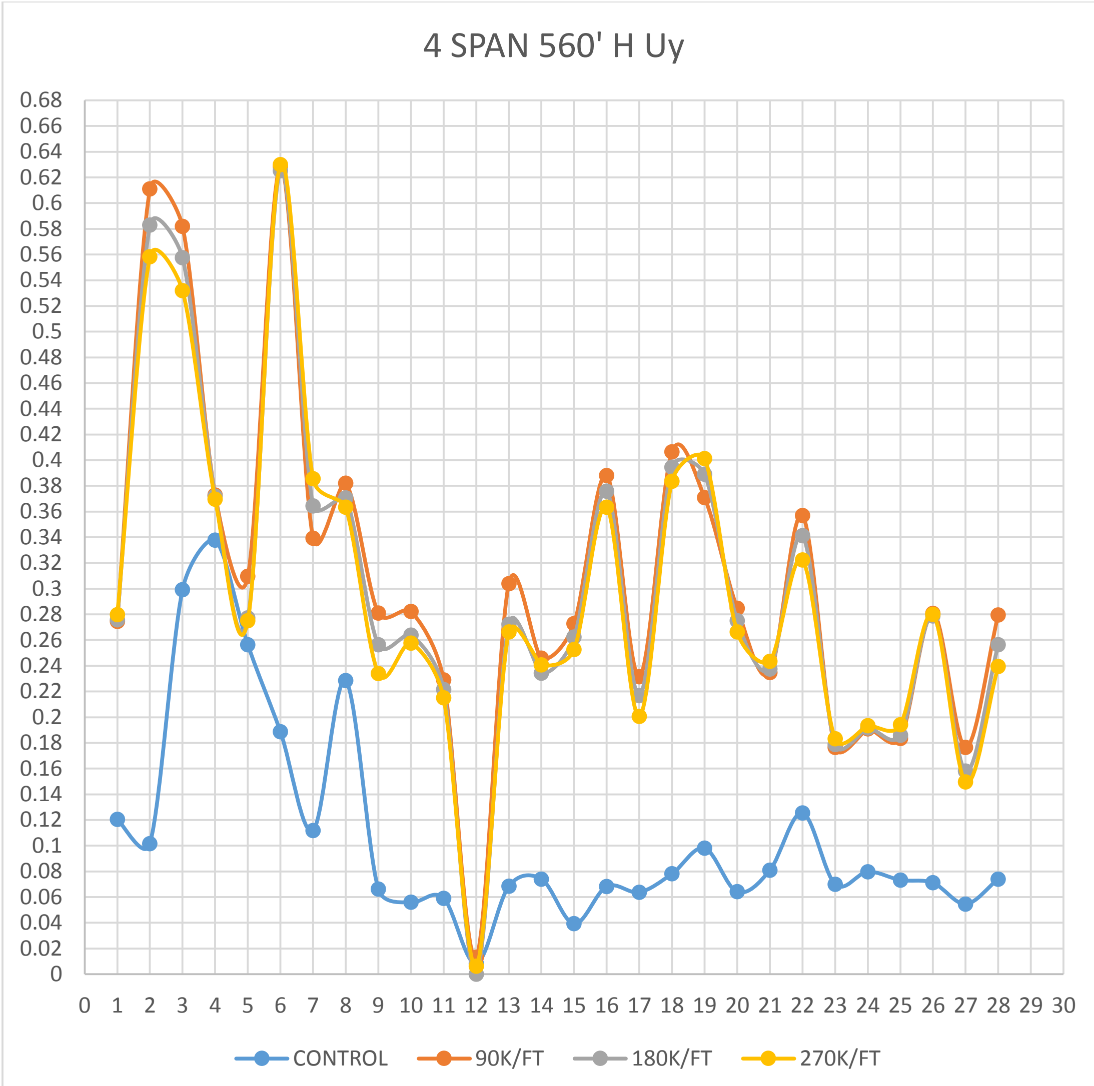


Fig. 3-88 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

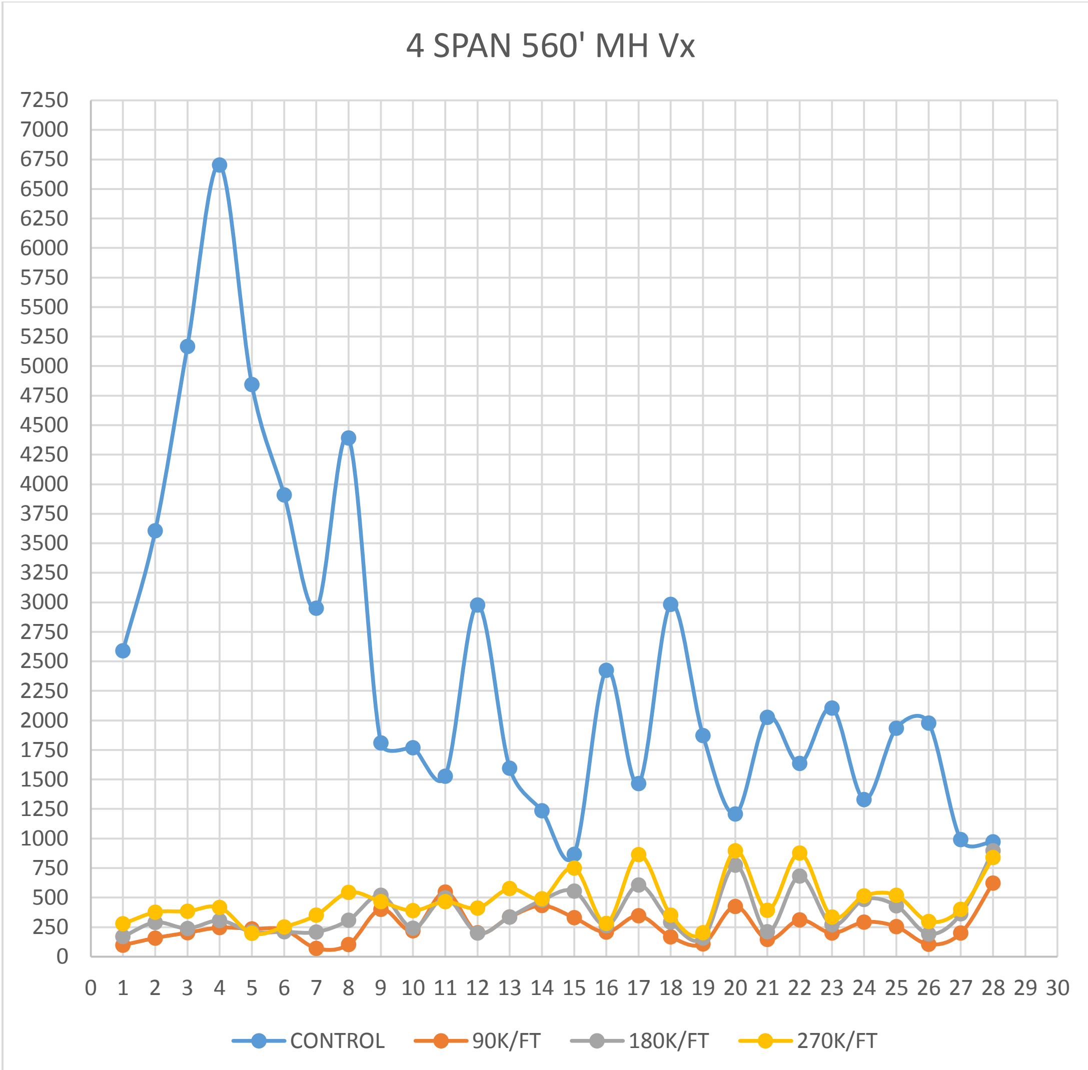


Fig. 3-89 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

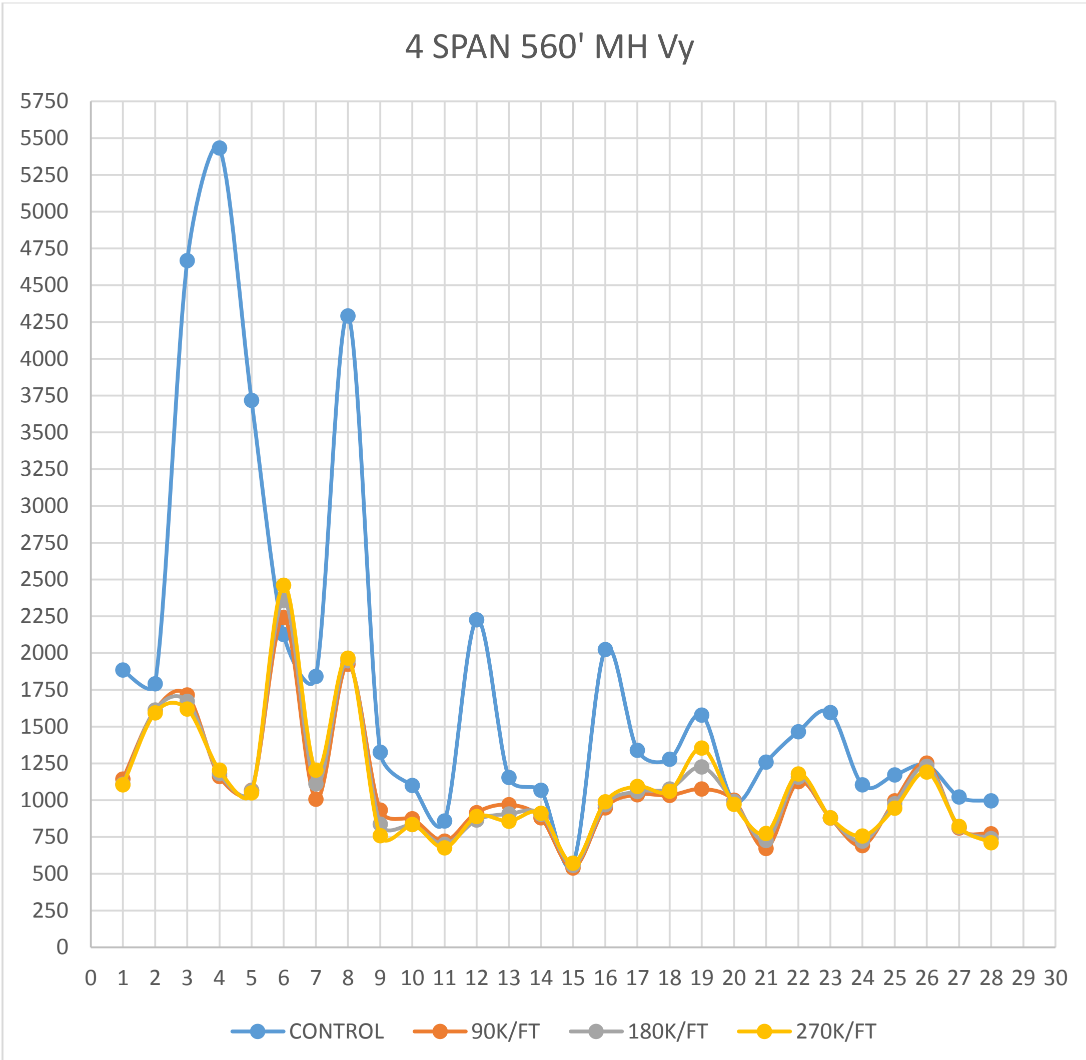


Fig. 3-90 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

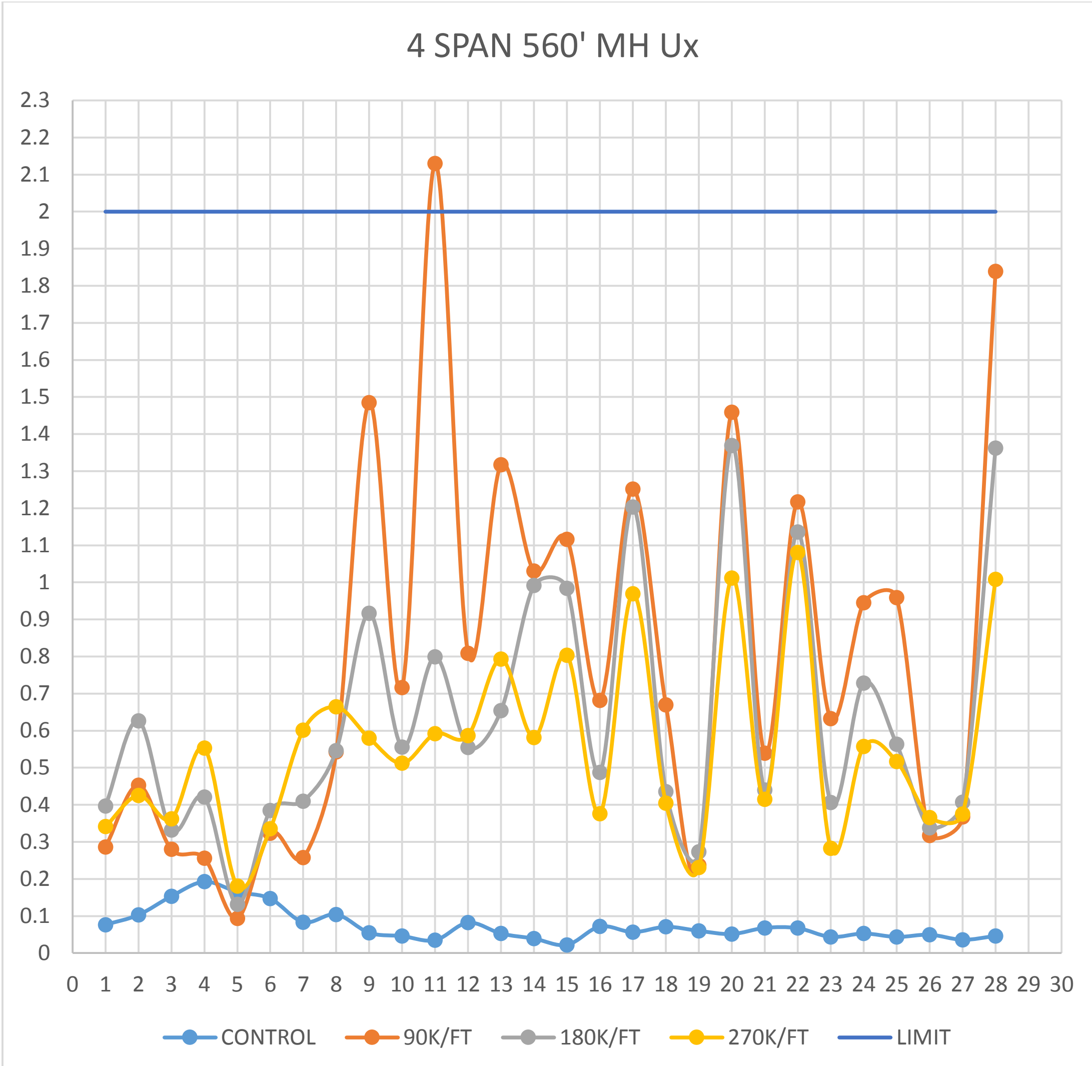


Fig. 3-91 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

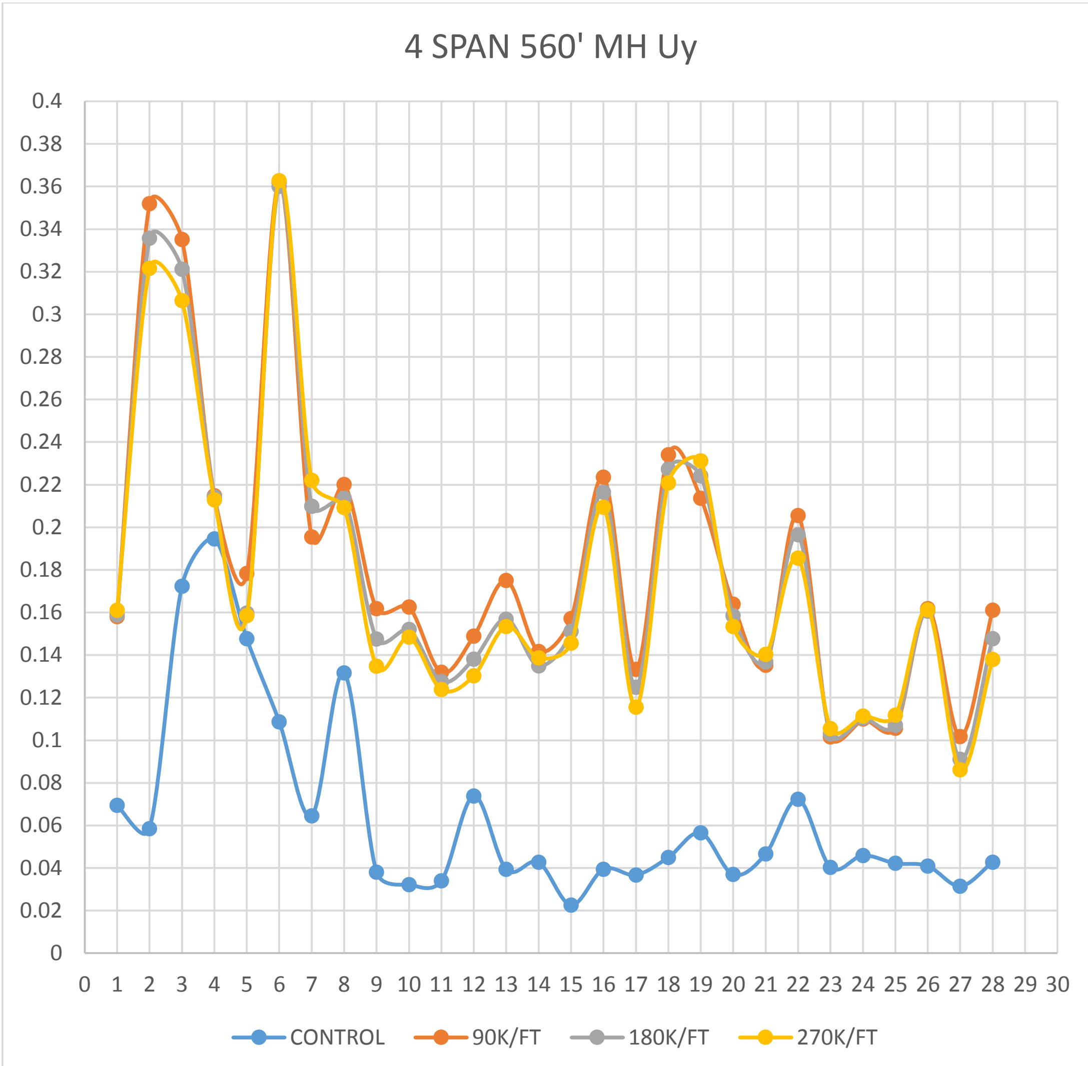


Fig. 3-92 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

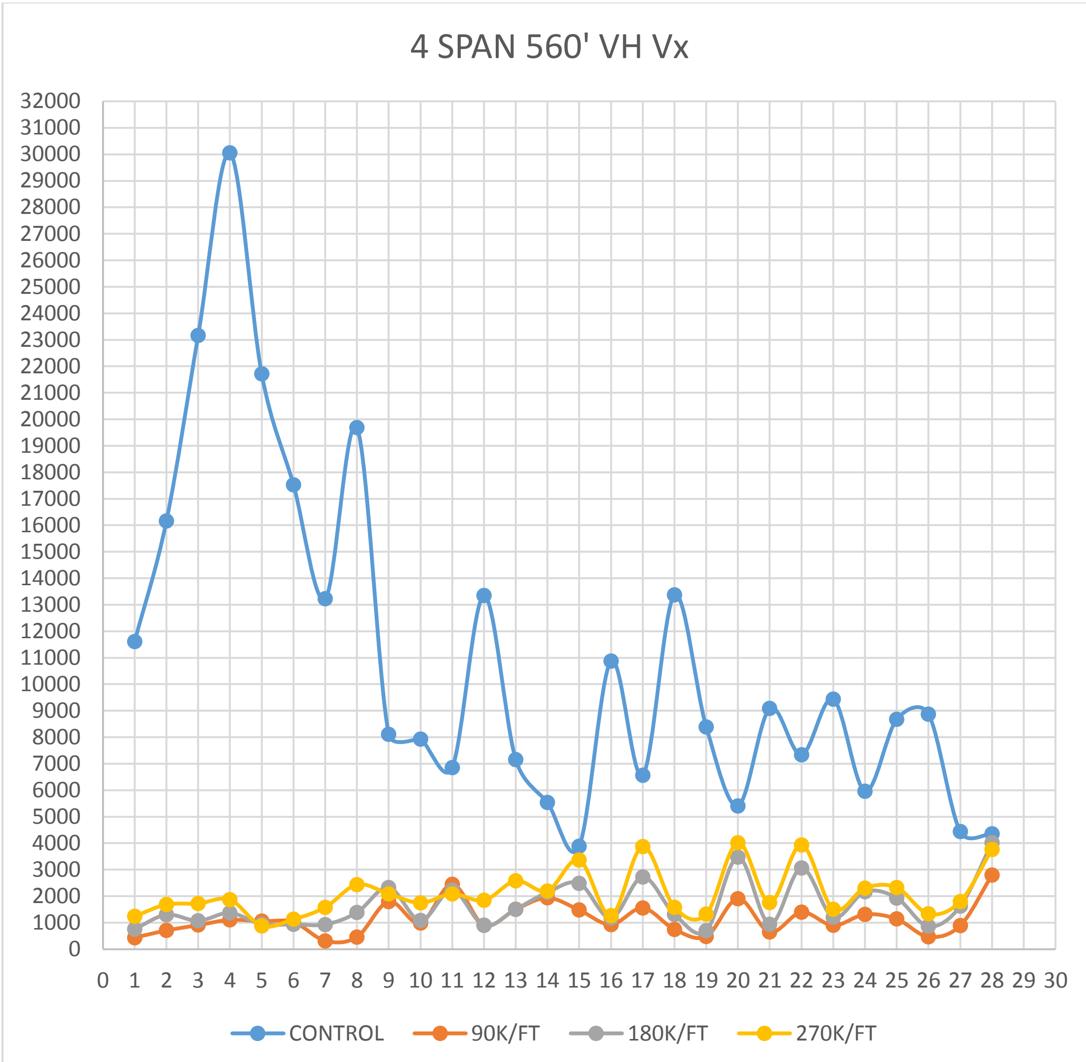


Fig. 3-93 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

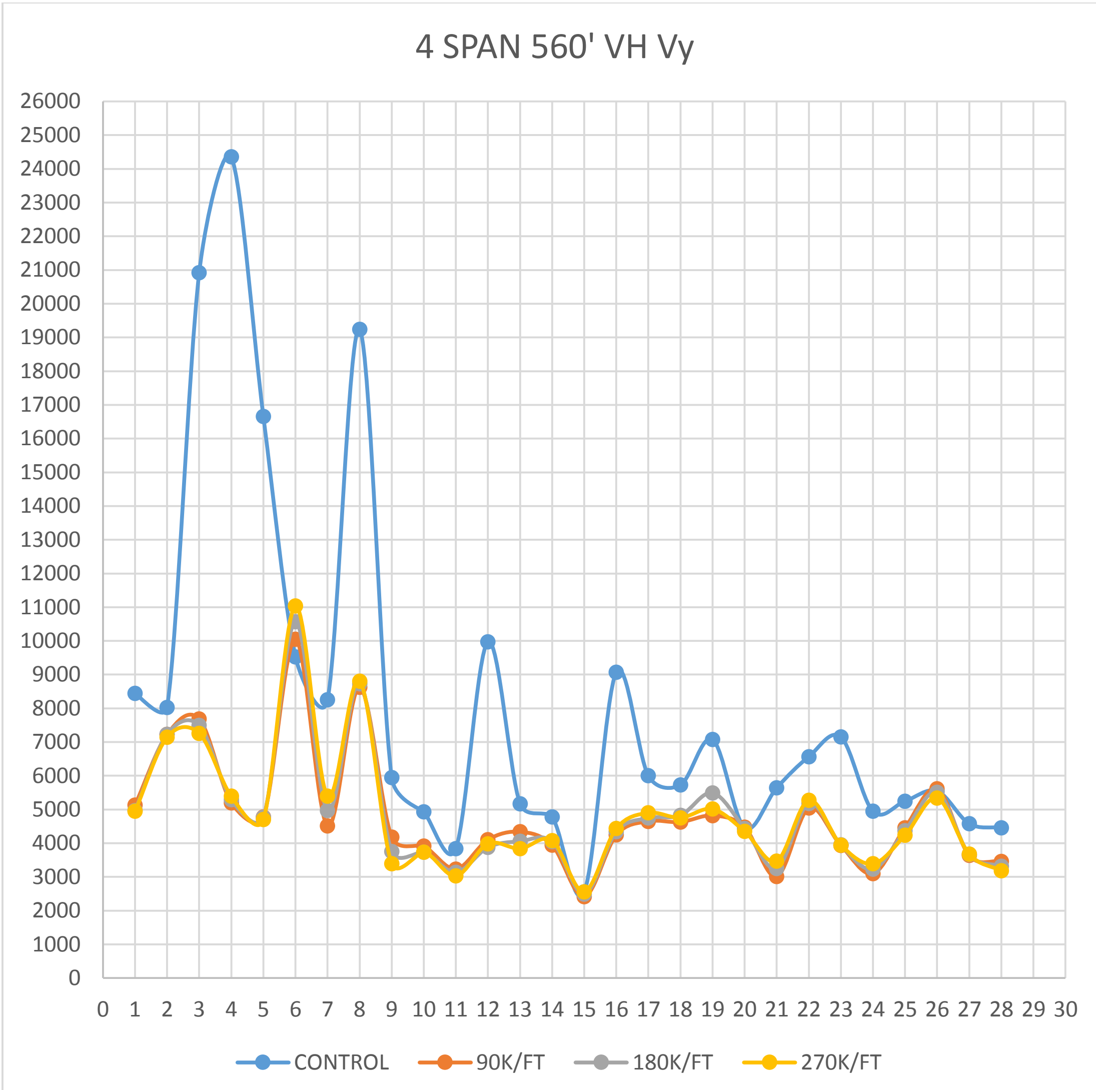


Fig. 3-94 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

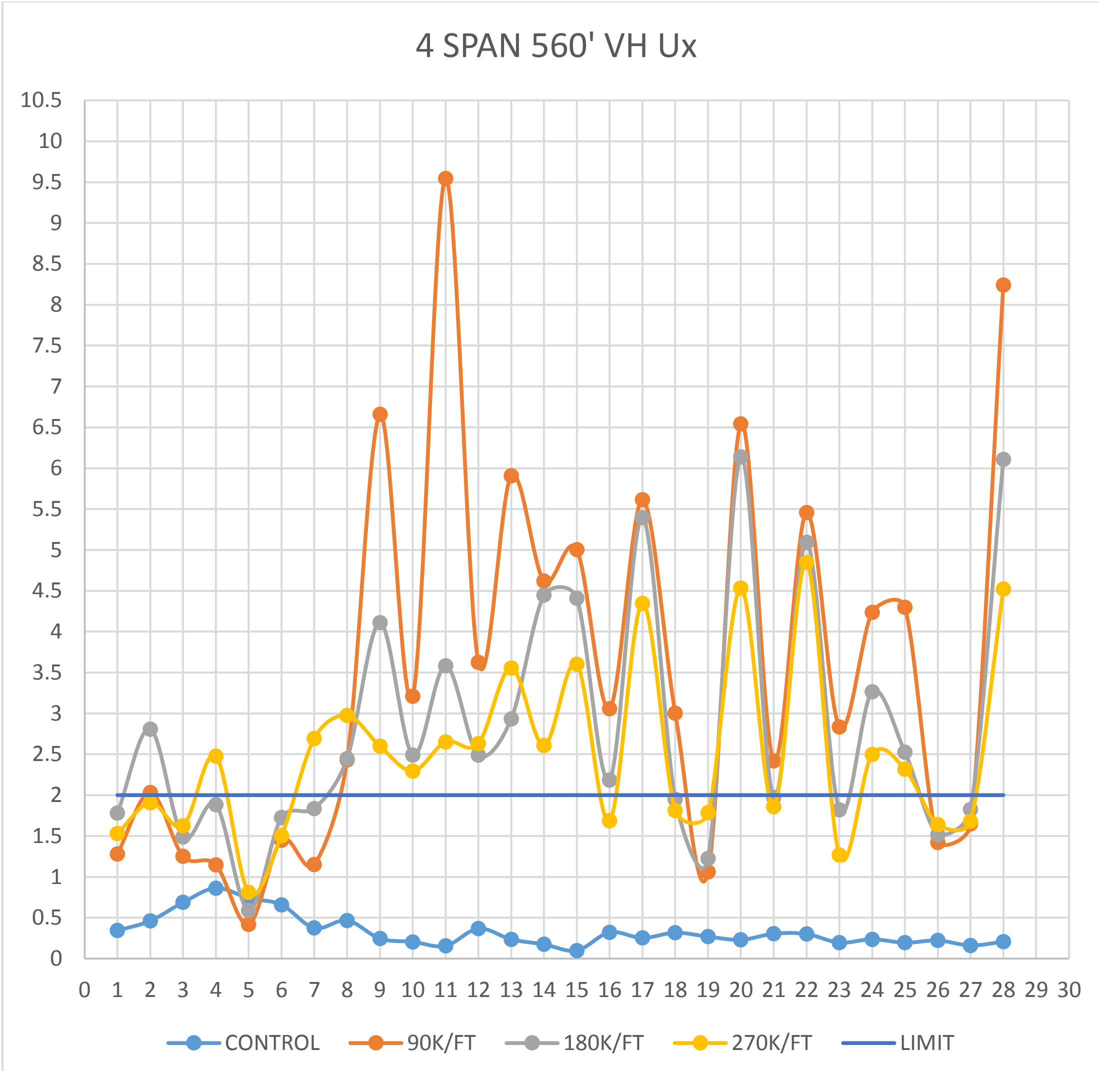


Fig. 3-95 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

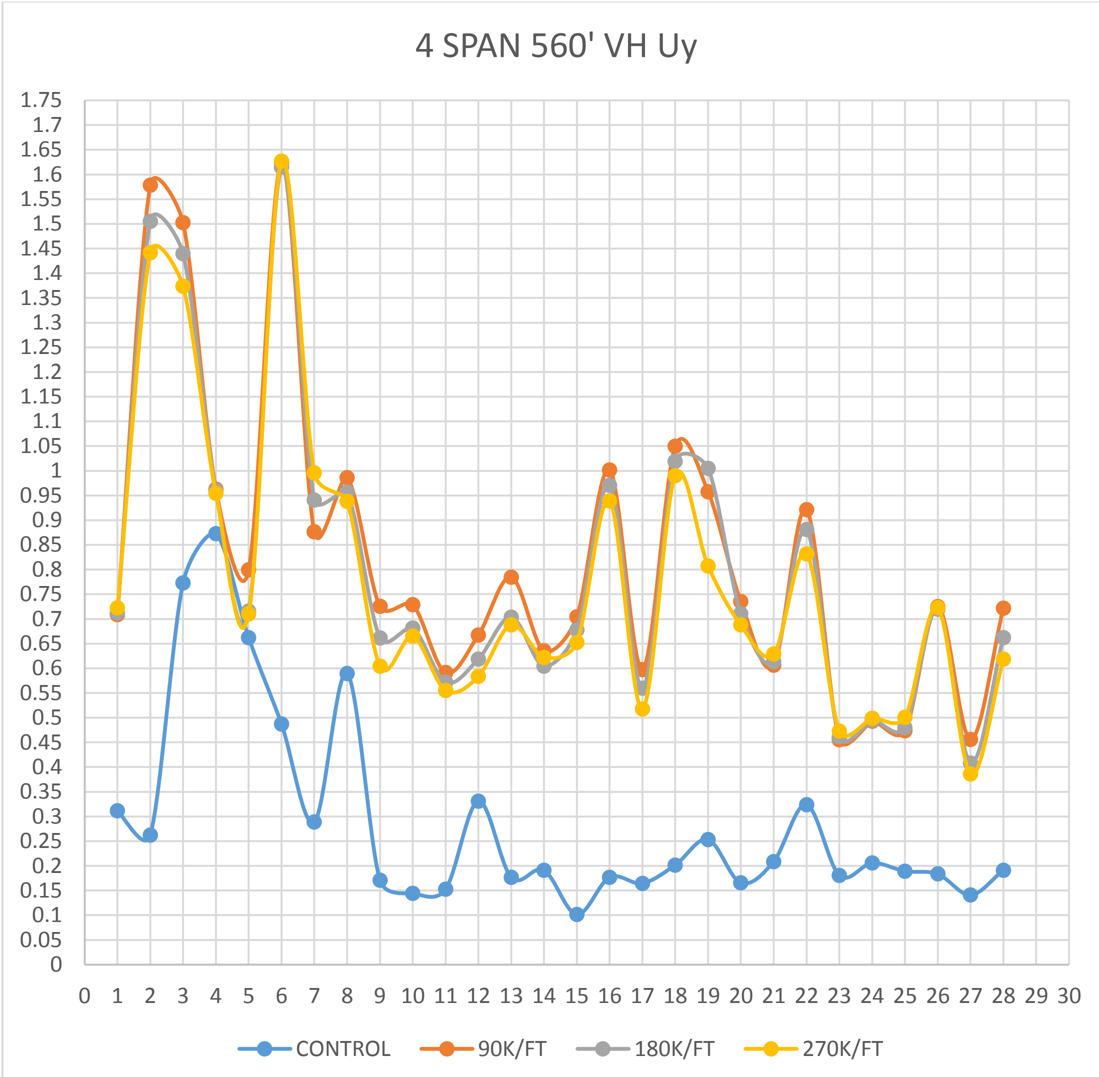


Fig. 3-96 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that all three stiffnesses can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 30053.76

90 K/Ft = 2793.931

180 K/Ft = 4014.938

270 K/Ft = 4019.922

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

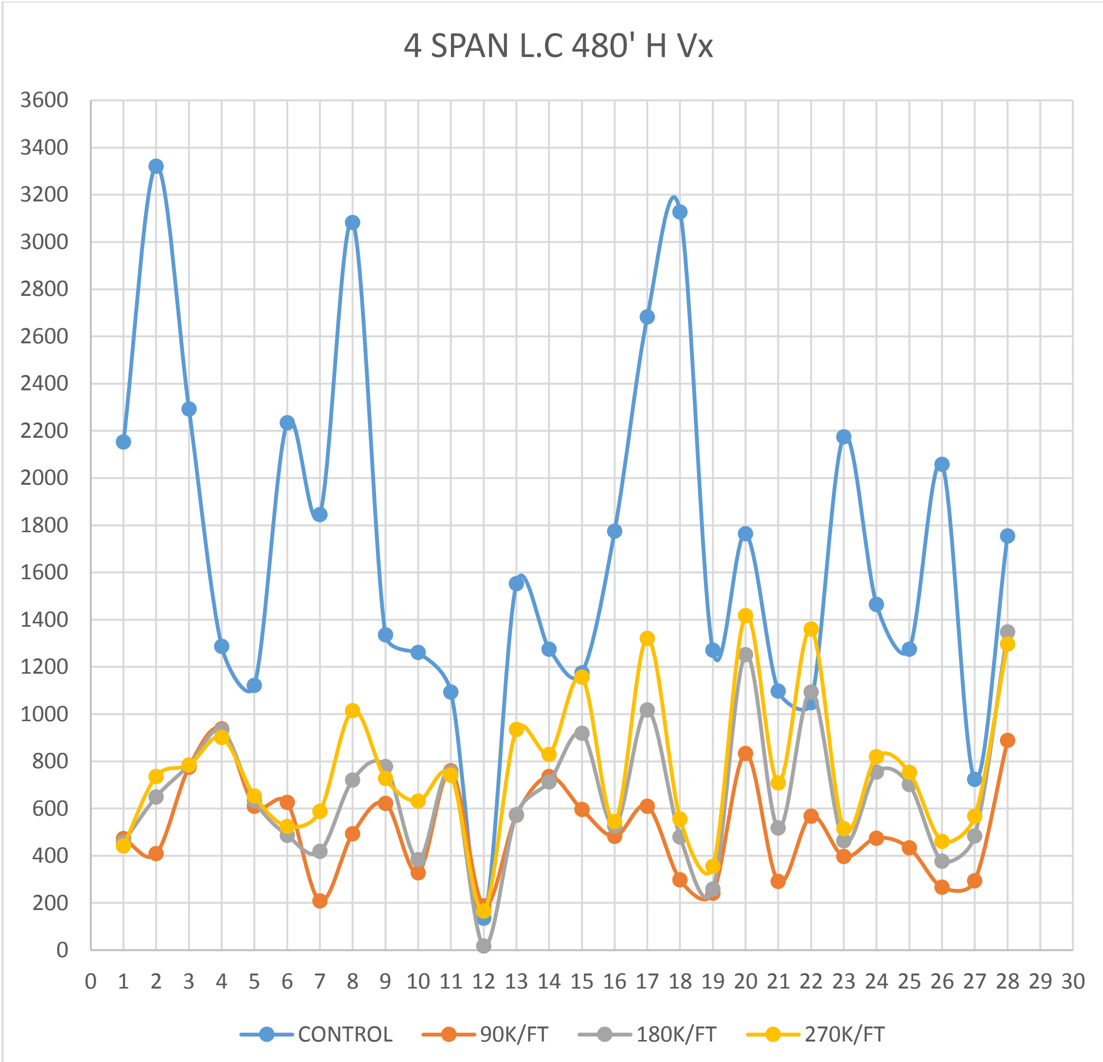


Fig. 3-97 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

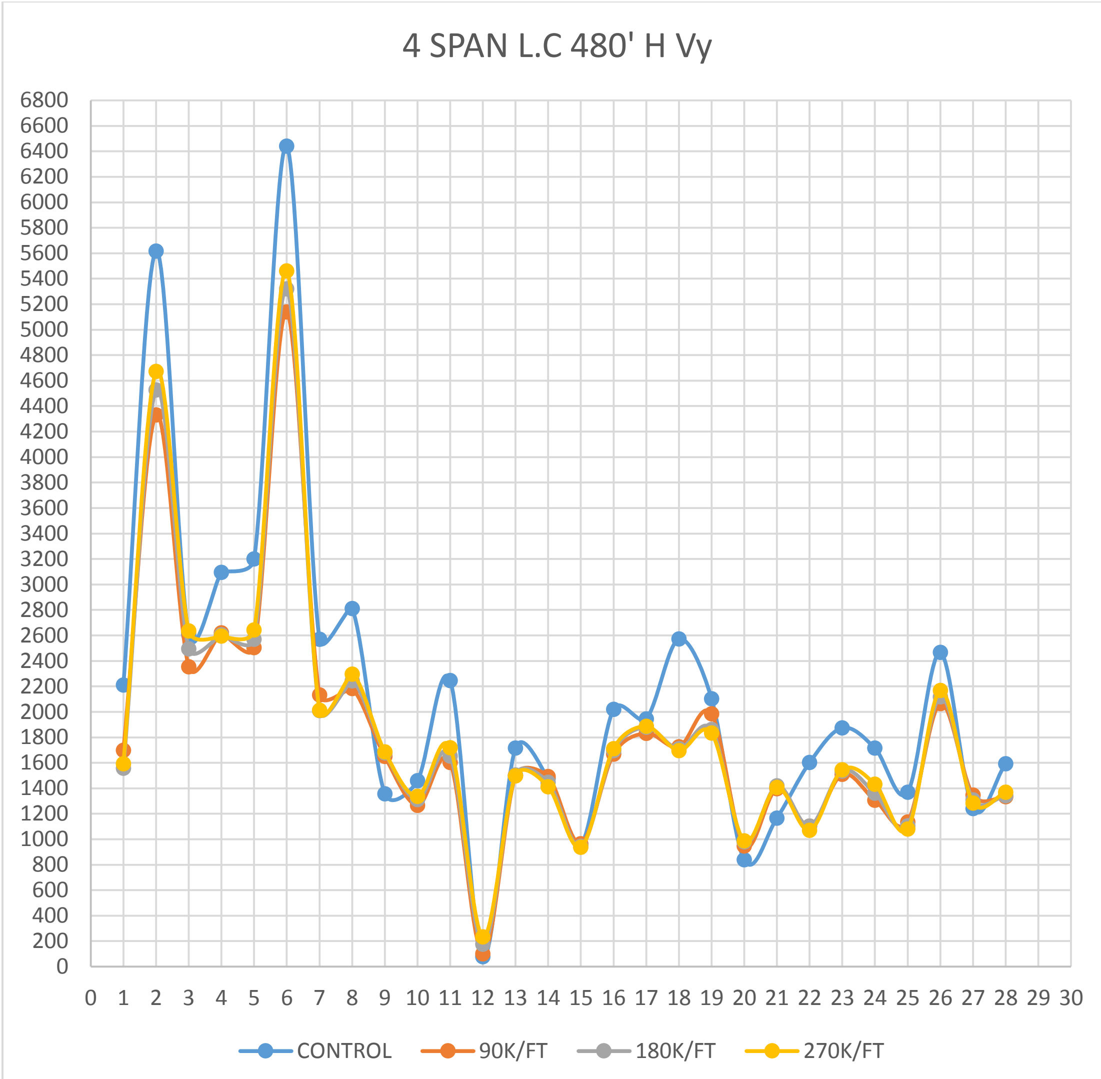


Fig. 3-98 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

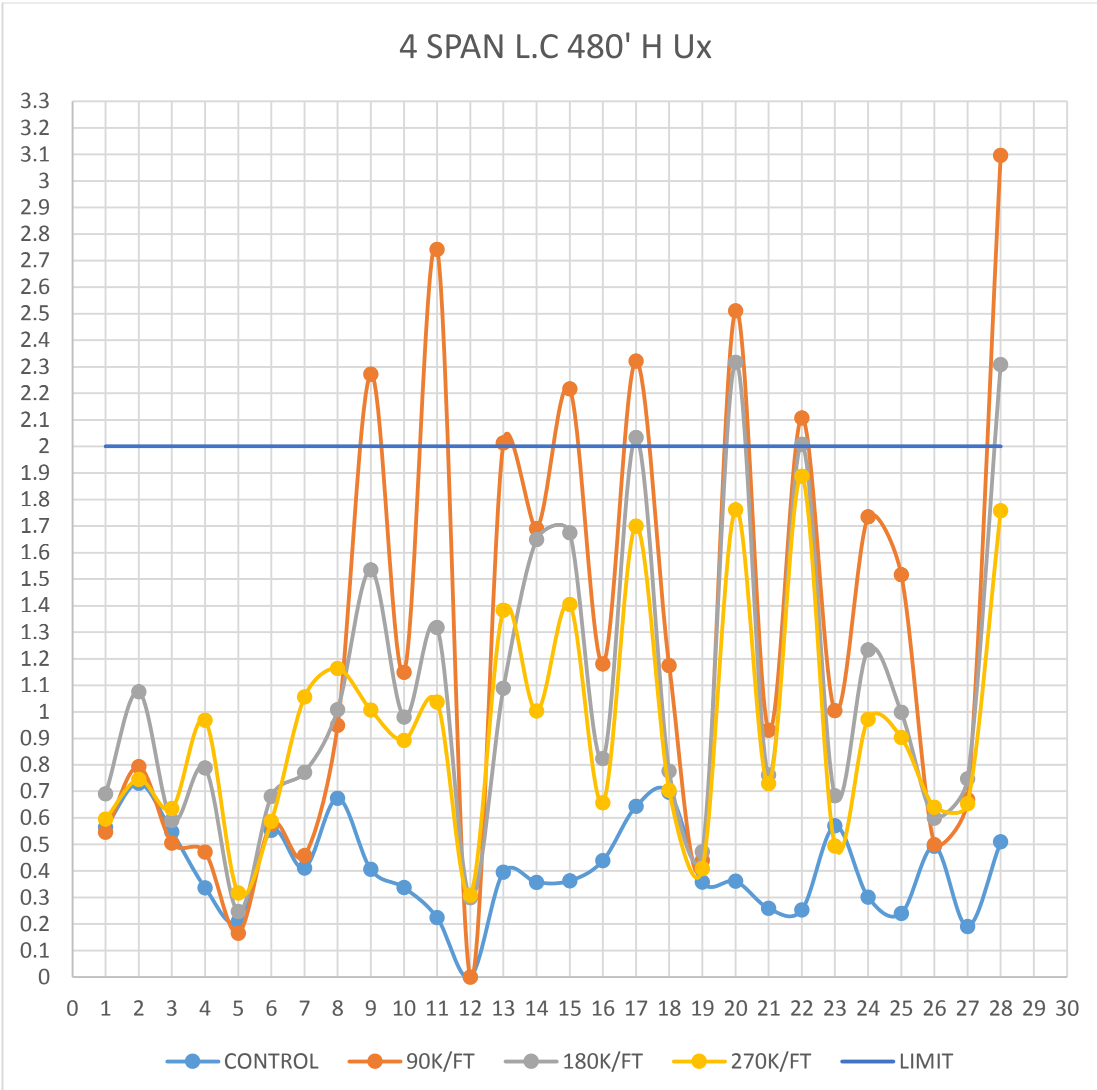


Fig. 3-99 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

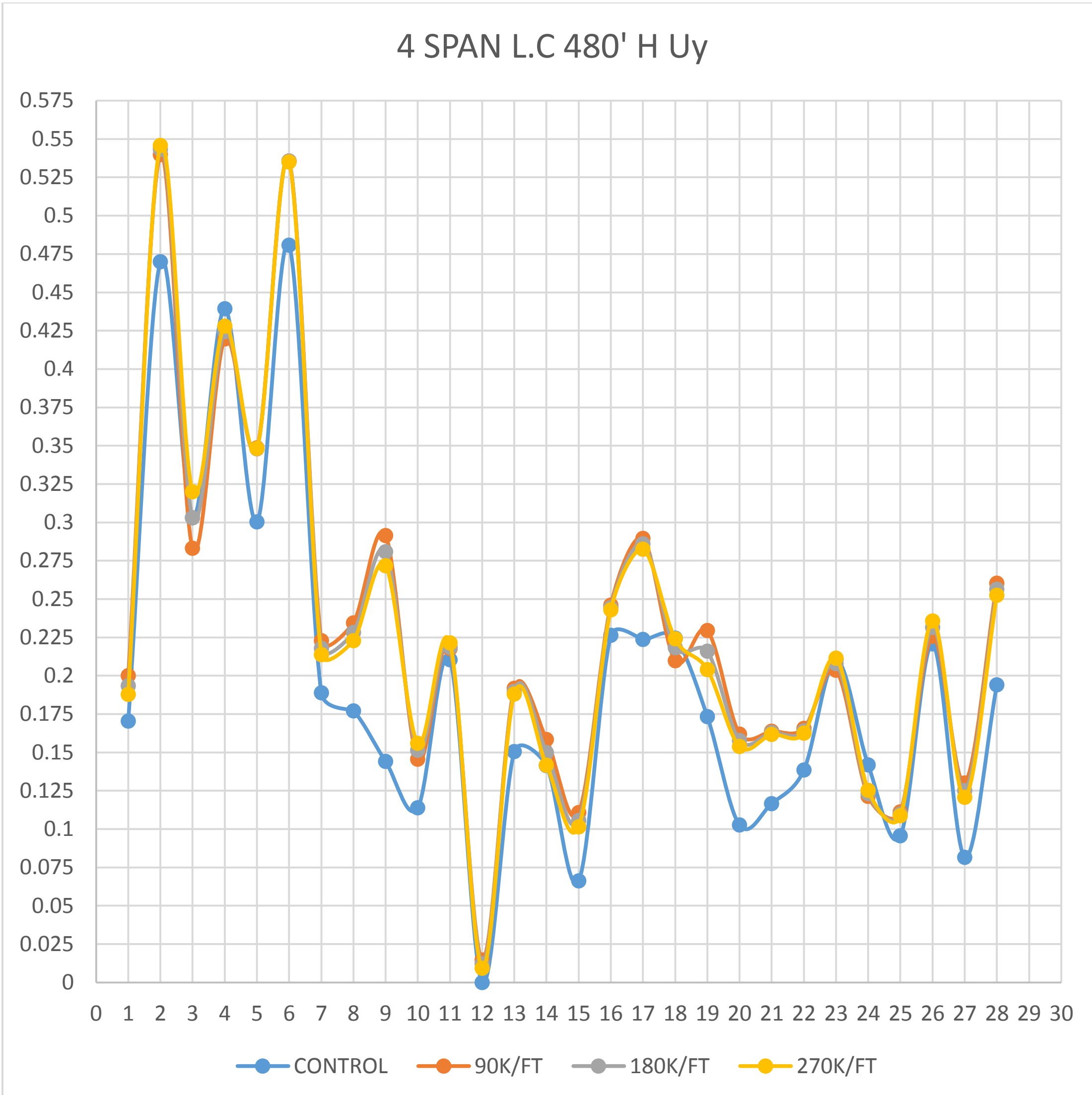


Fig. 3-100 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

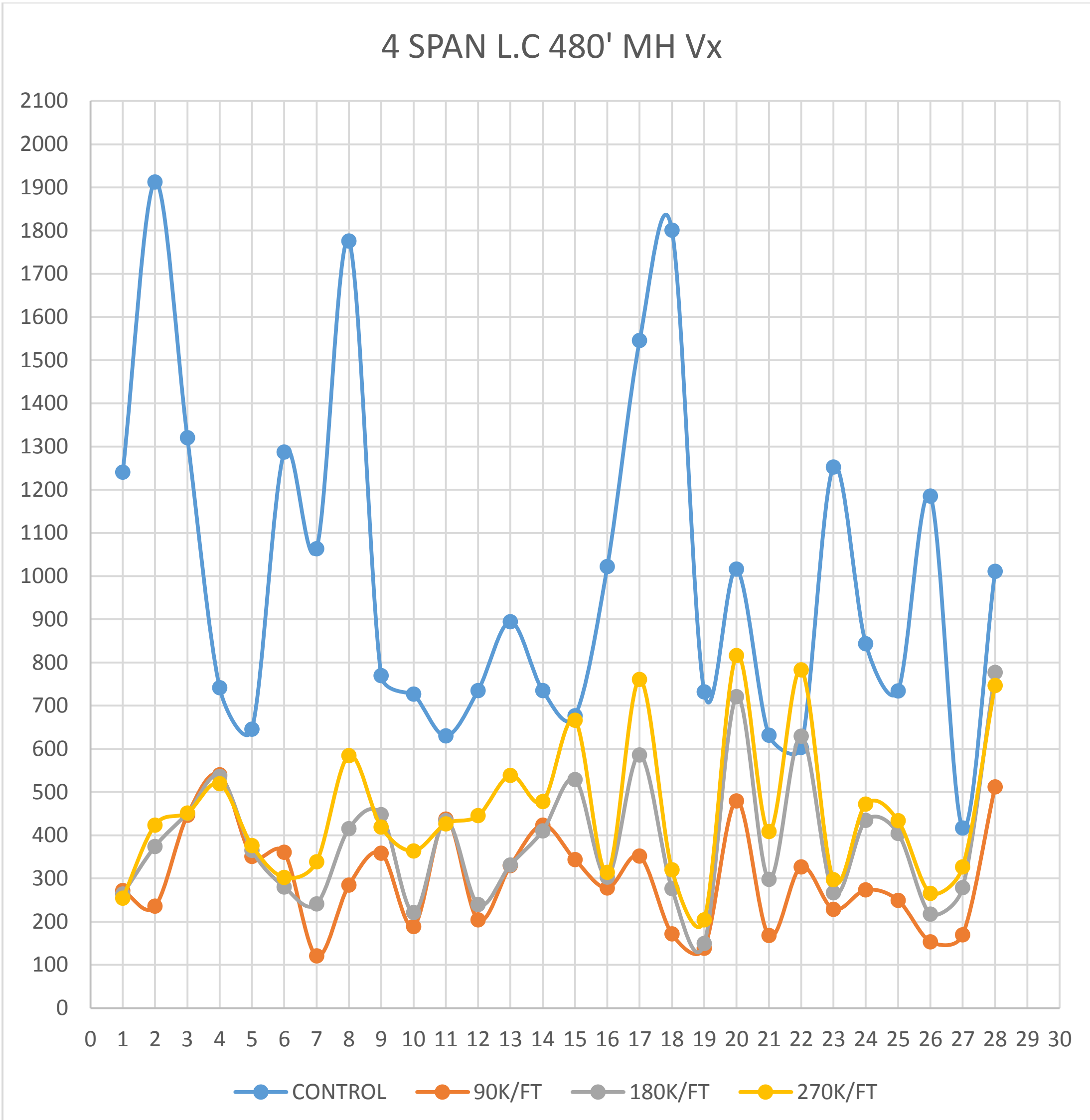


Fig. 3-101 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

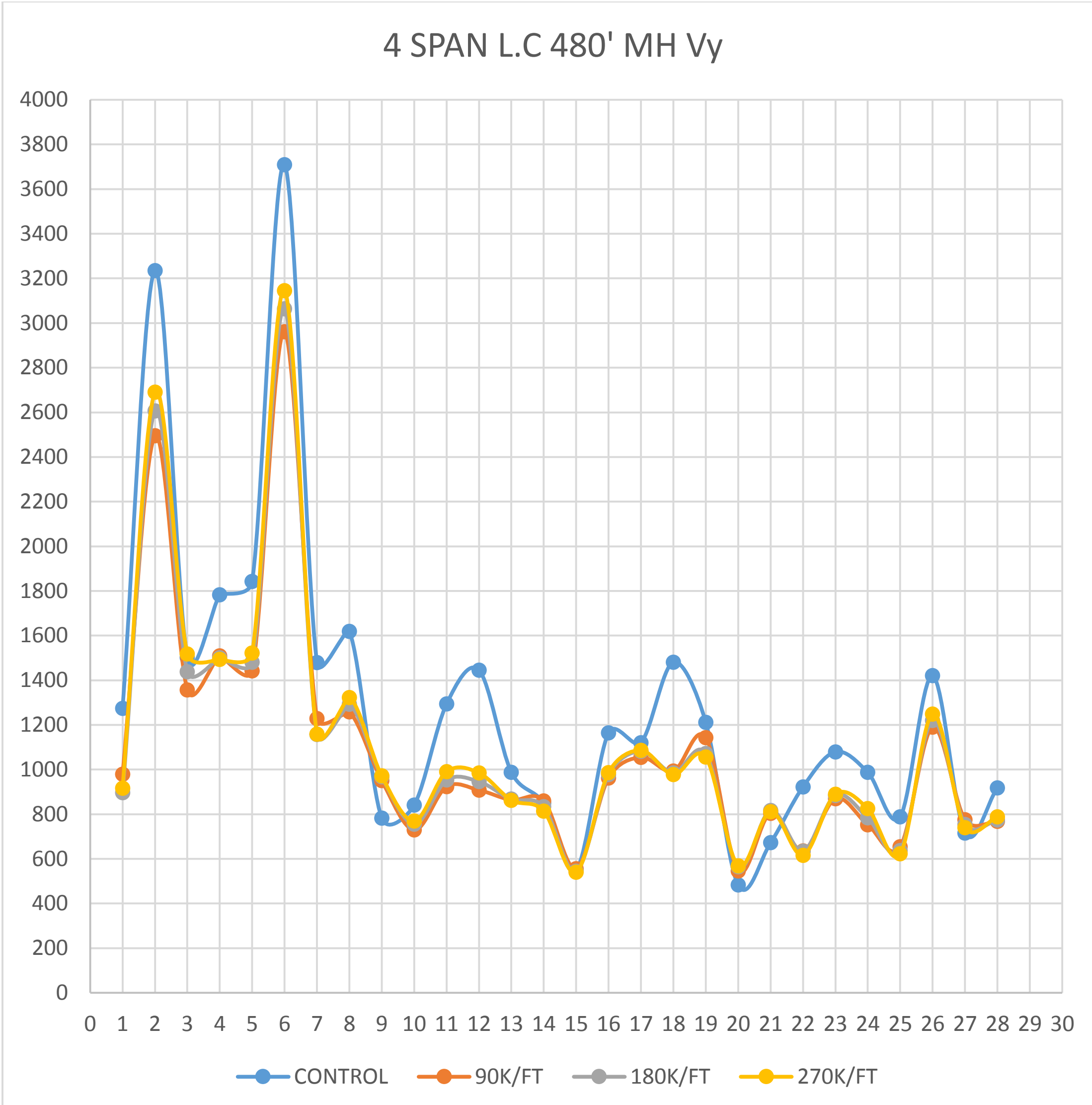


Fig. 3-102 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

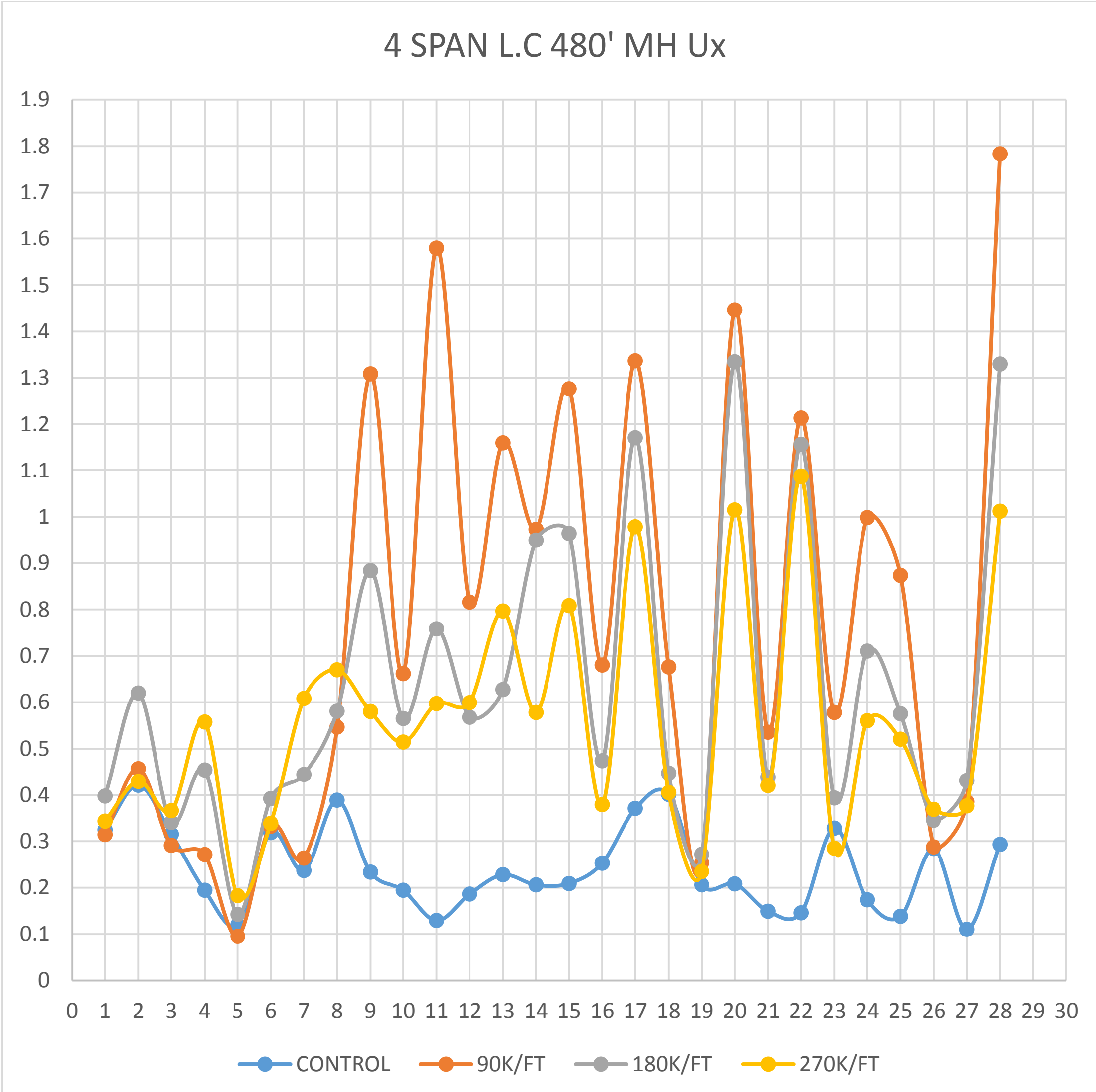


Fig. 3-103 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

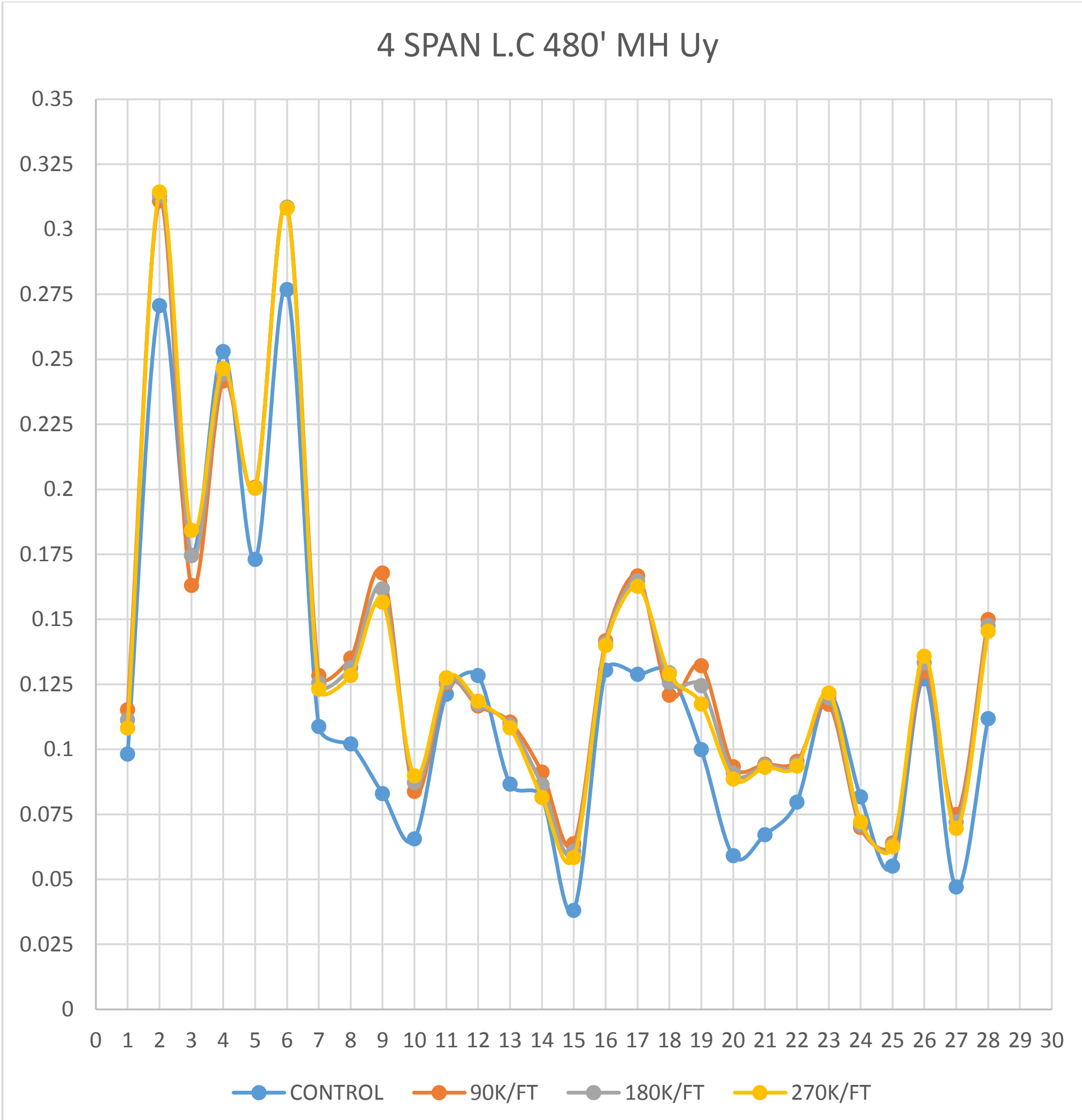


Fig. 3-104 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

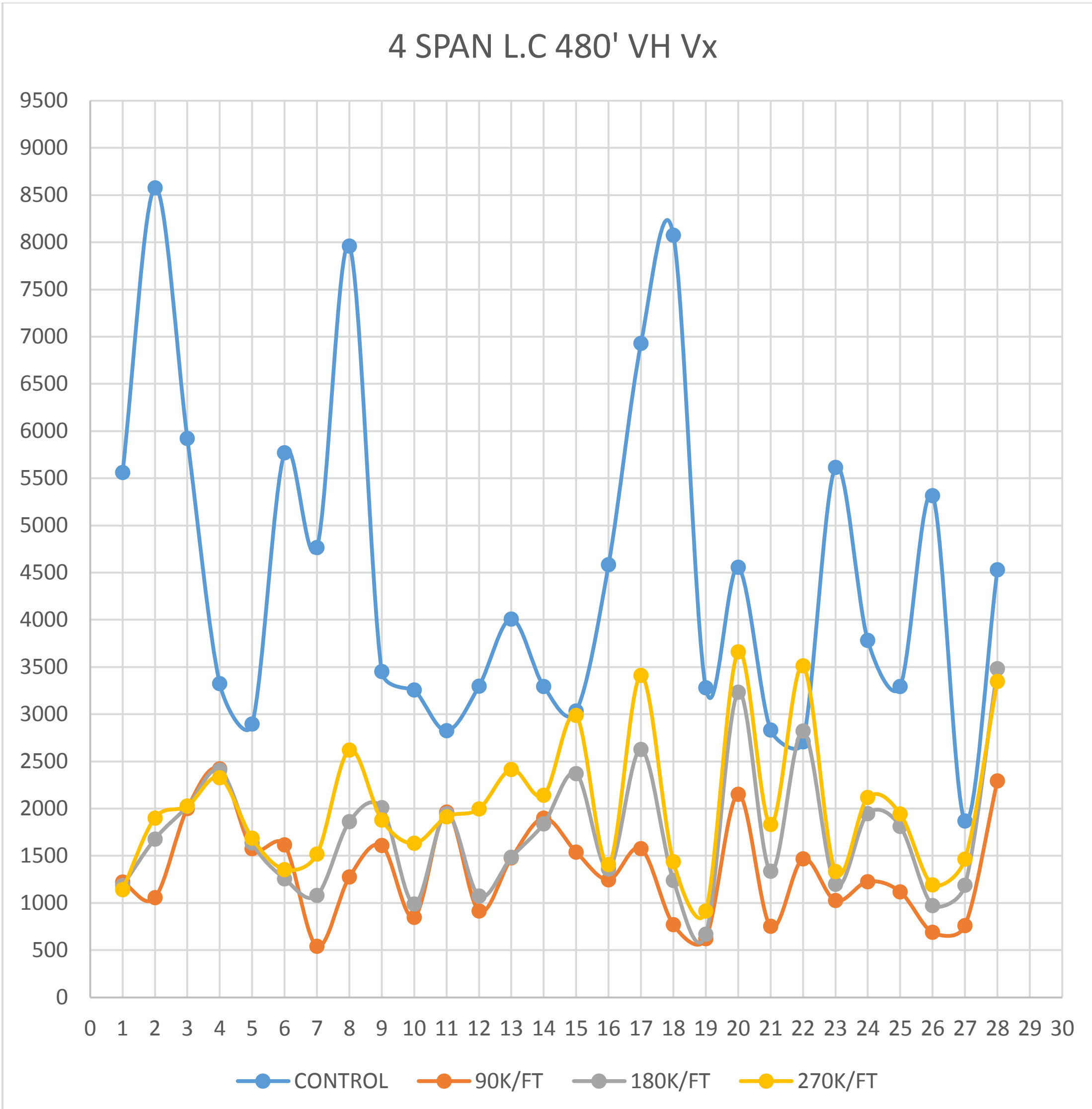


Fig. 3-105 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

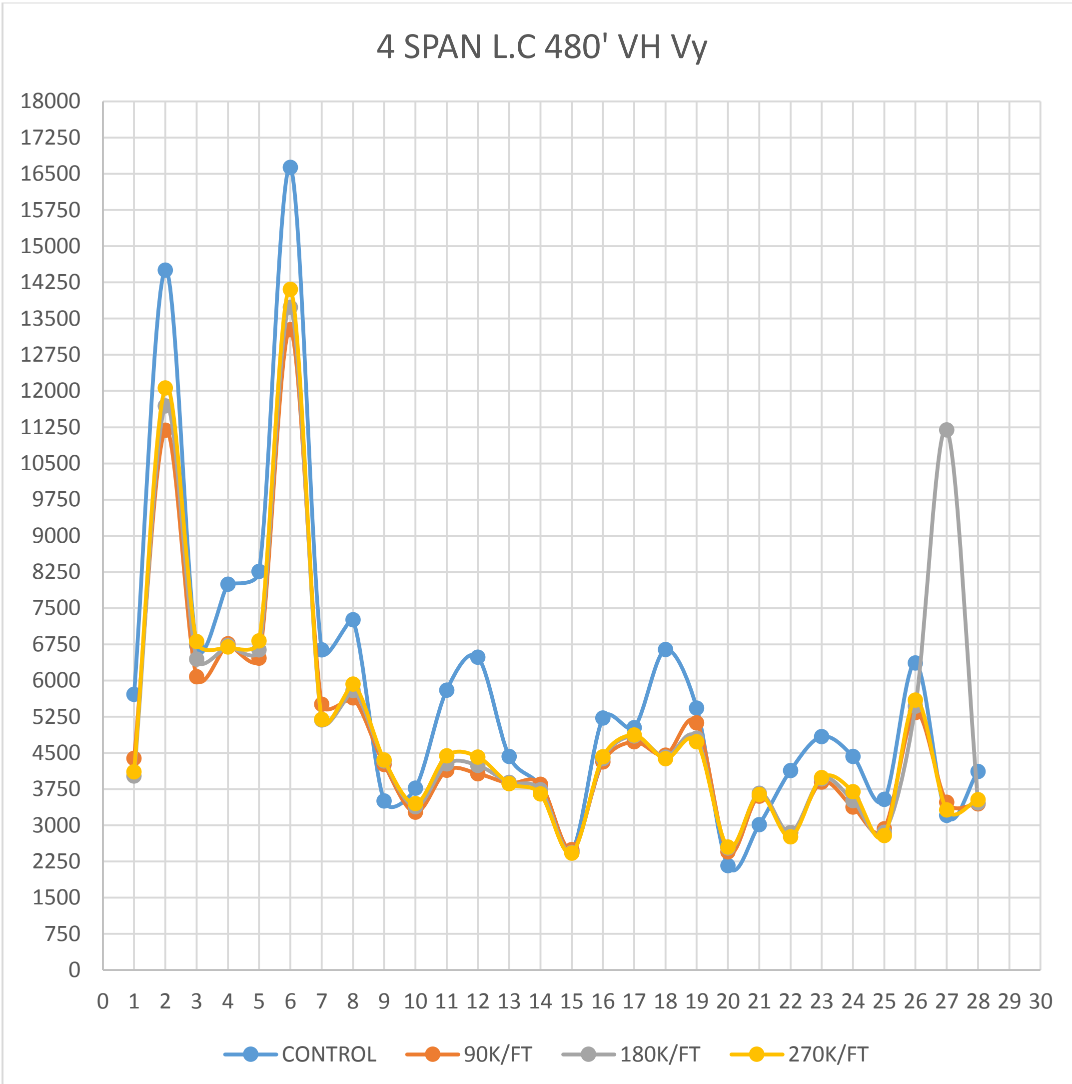


Fig. 3-106 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

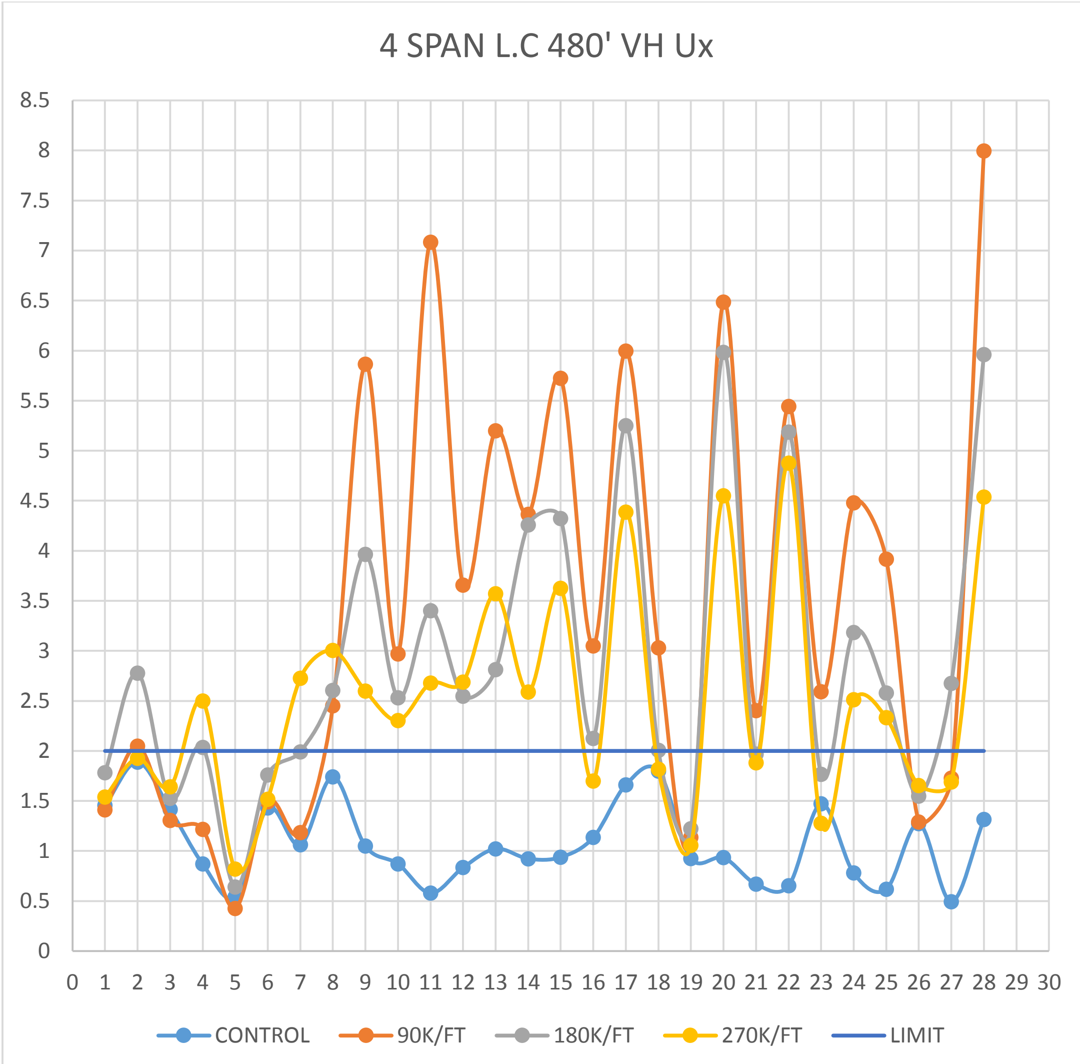


Fig. 3-107 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

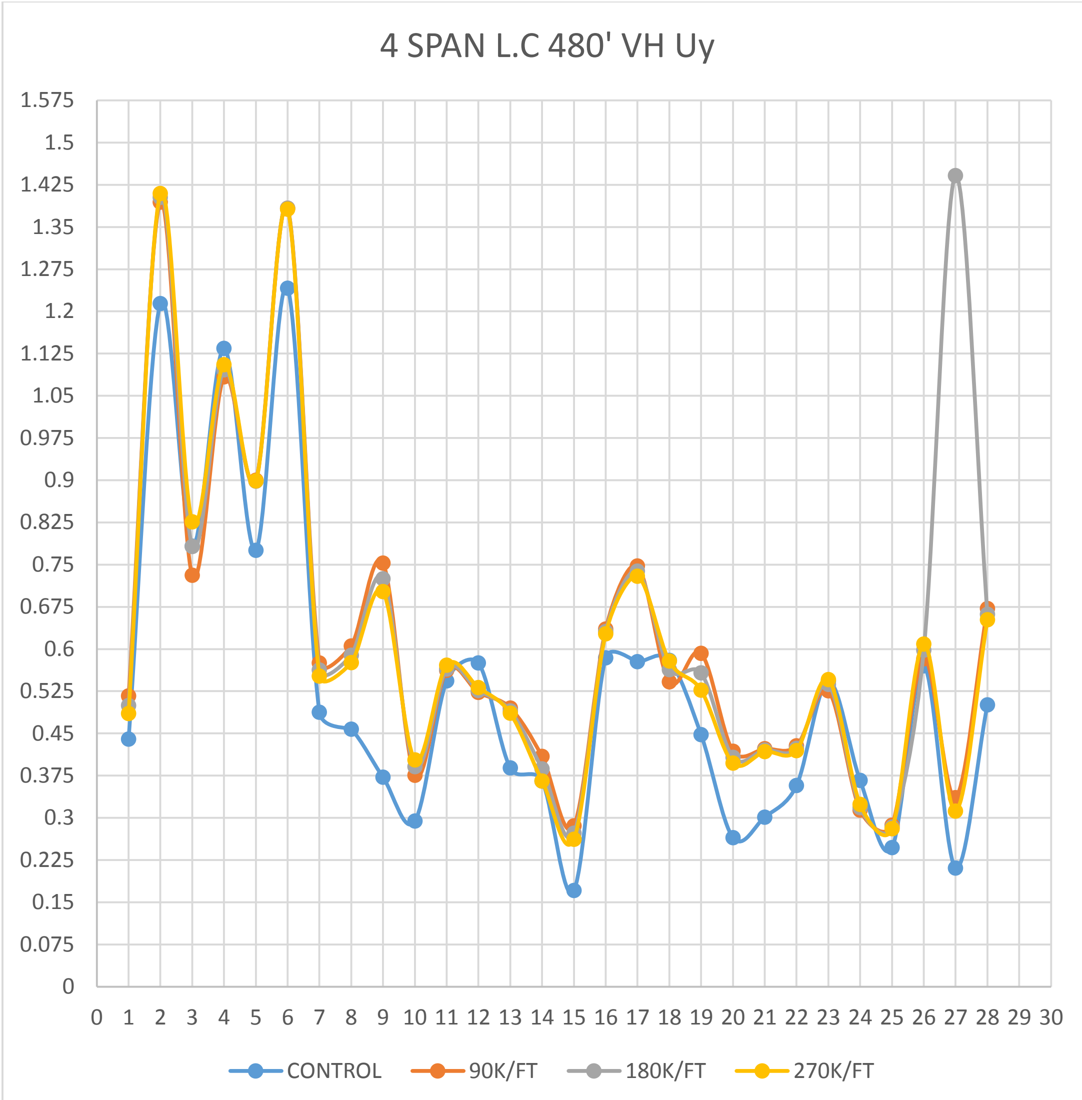


Fig. 3-108 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that all three stiffnesses can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 8575.727

90 K/Ft = 2422.484

180 K/Ft = 3481.847

270 K/Ft = 3659.508

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

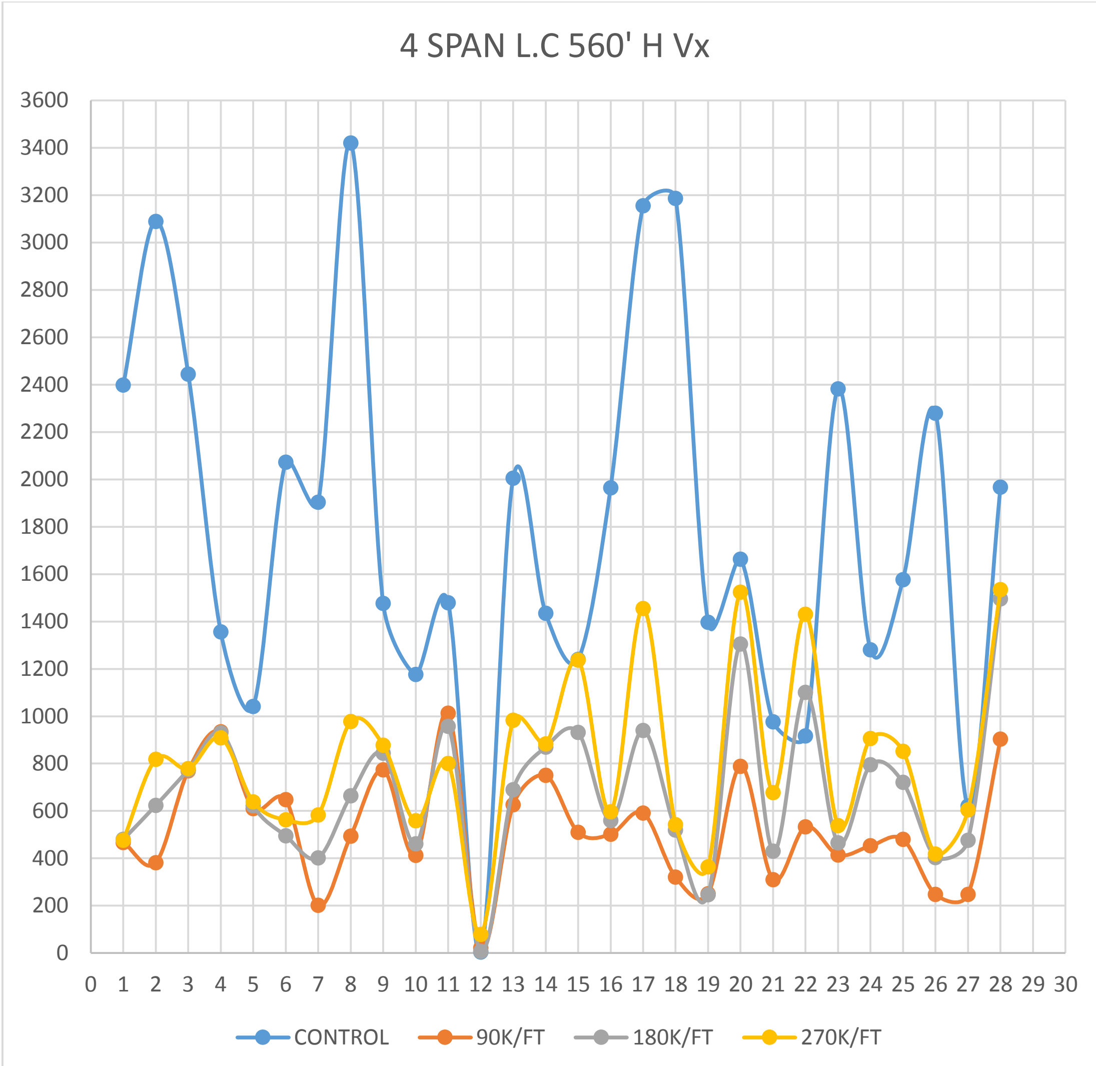


Fig. 3-109 Variation of longitudinal base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

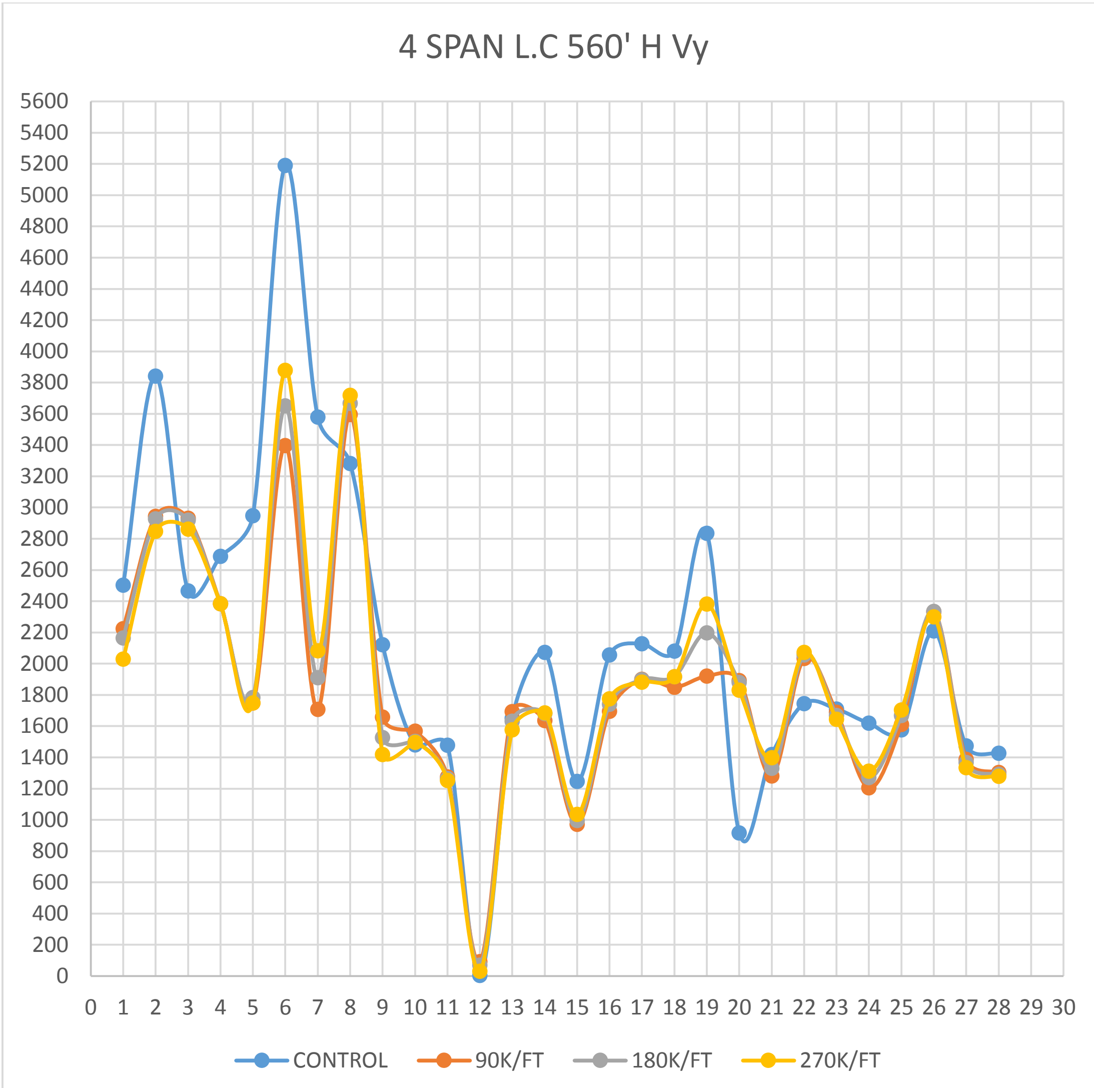


Fig. 3-110 Variation of transverse base shear with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

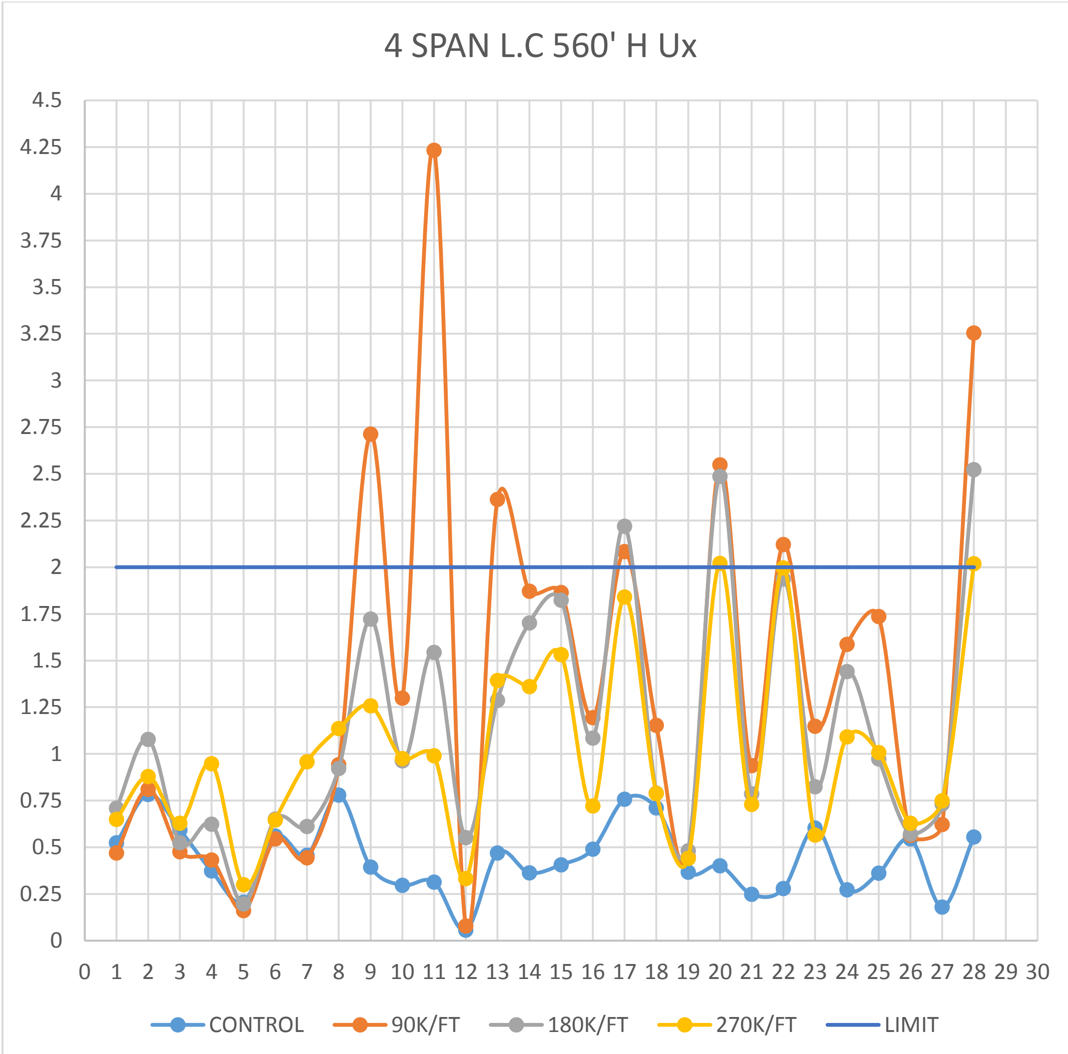


Fig. 3-111 Variation of longitudinal displacement with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

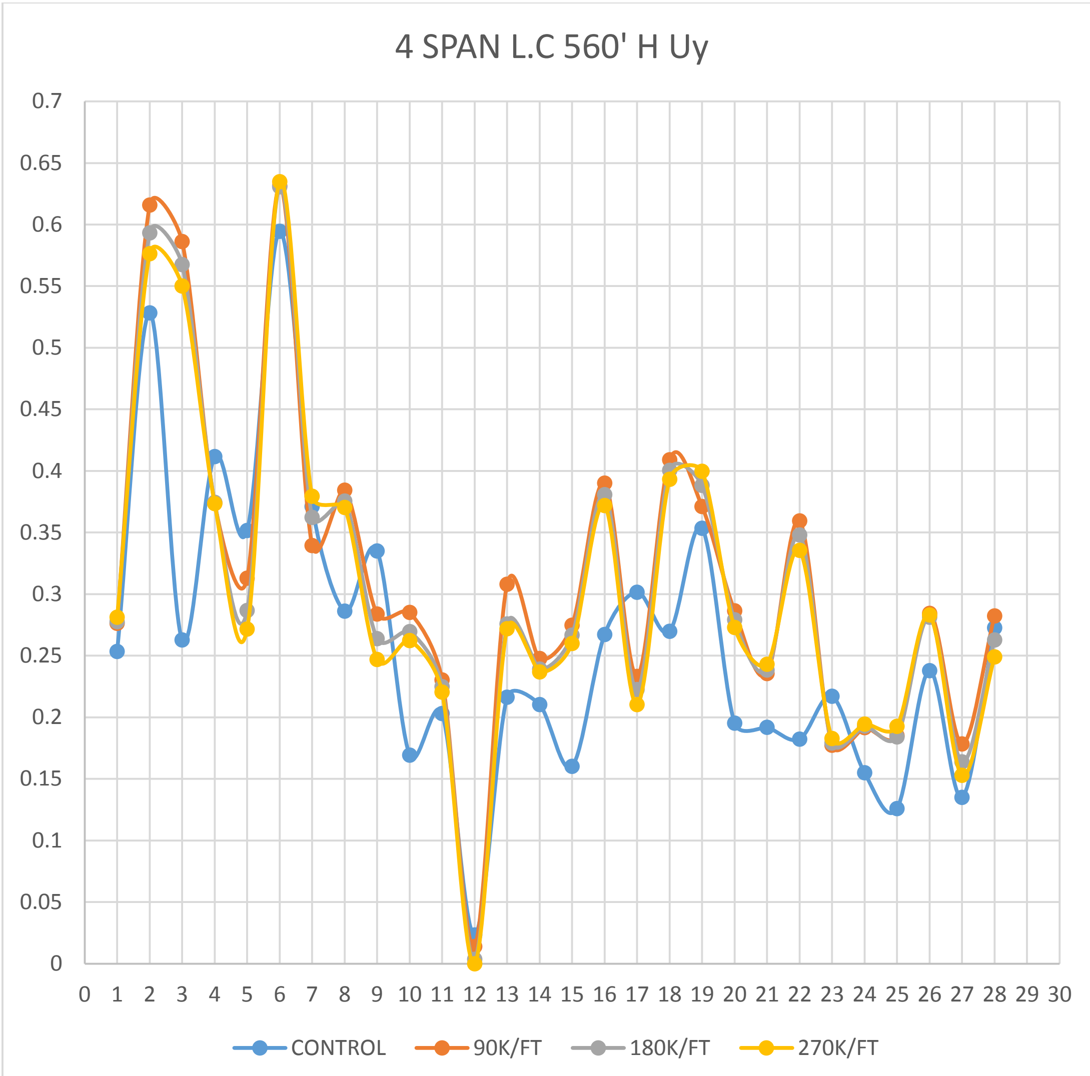


Fig. 3-112 Variation of transverse displacement with isolator stiffness for high intensity Near Field earthquakes, for the four span bridge.

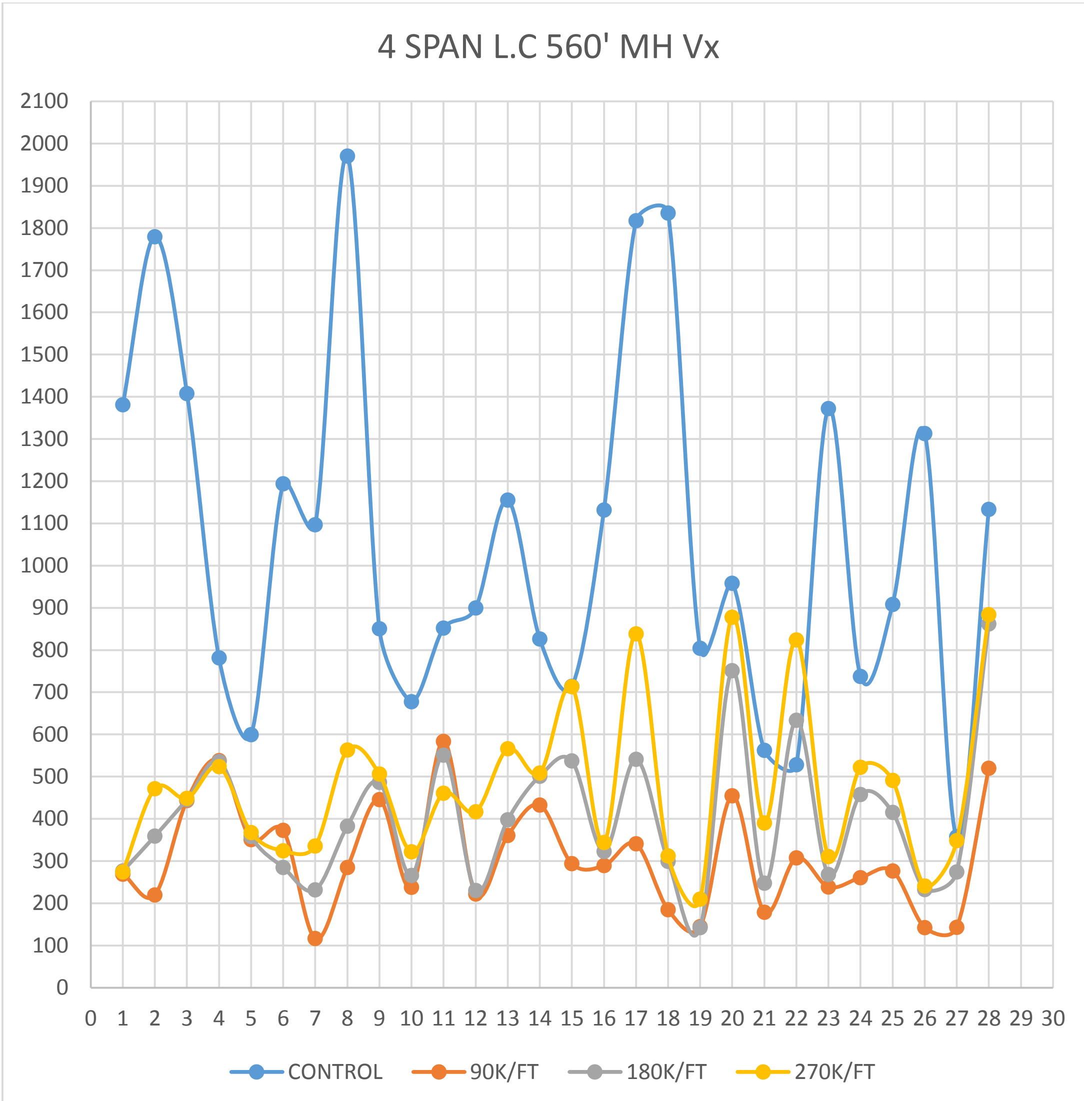


Fig. 3-113 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

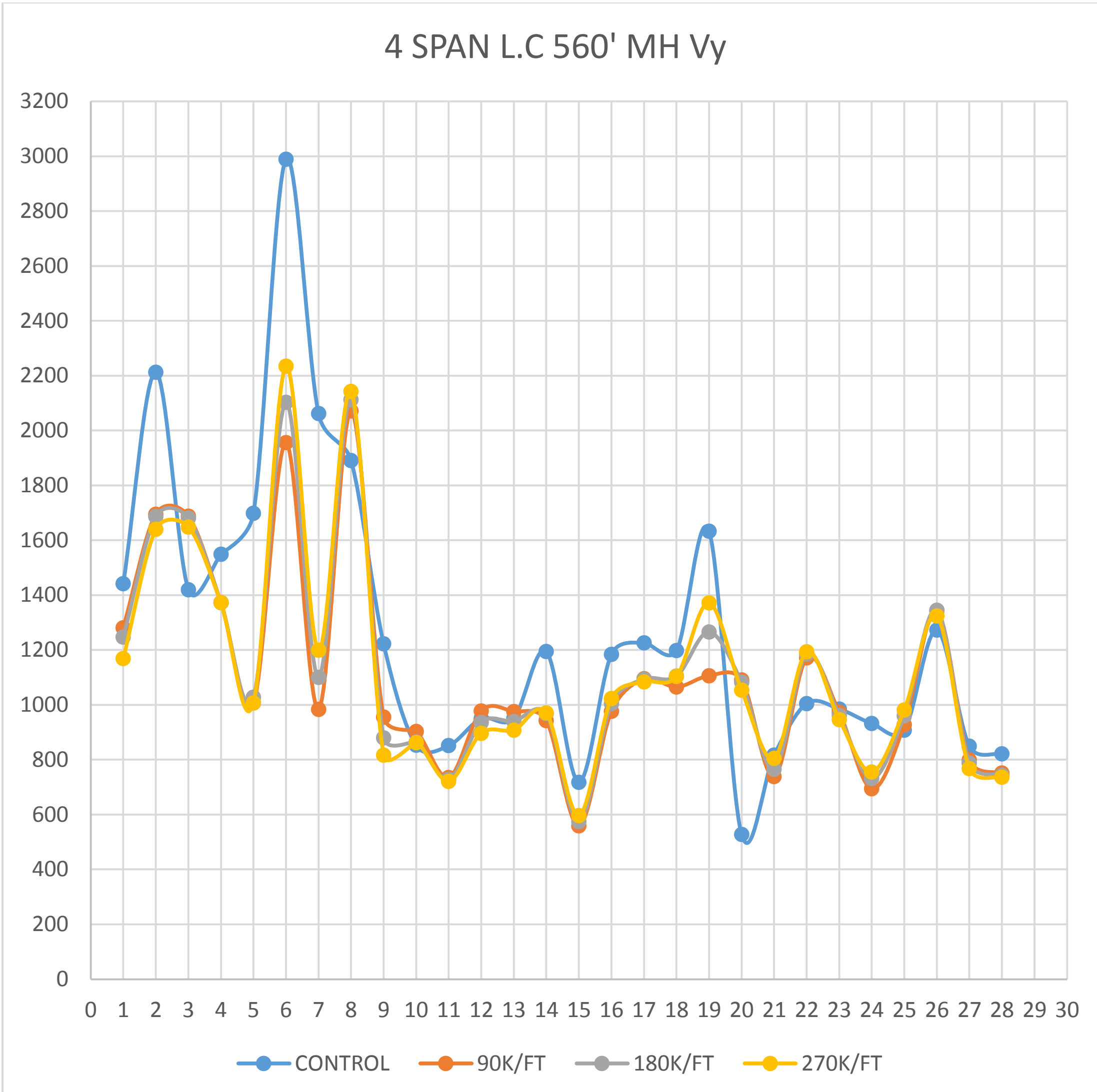


Fig. 3-114 Variation of transverse base shear with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

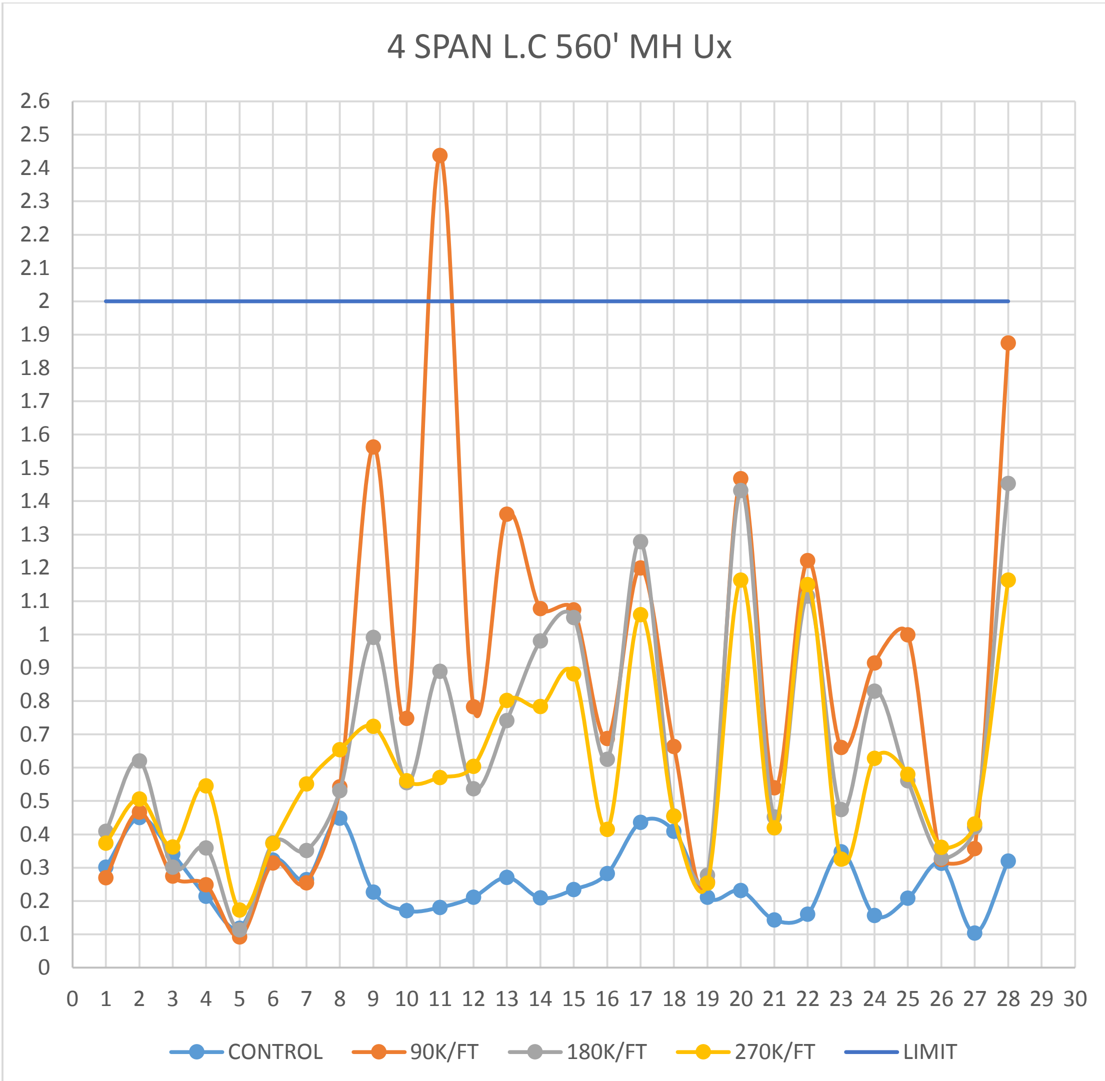


Fig. 3-115 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

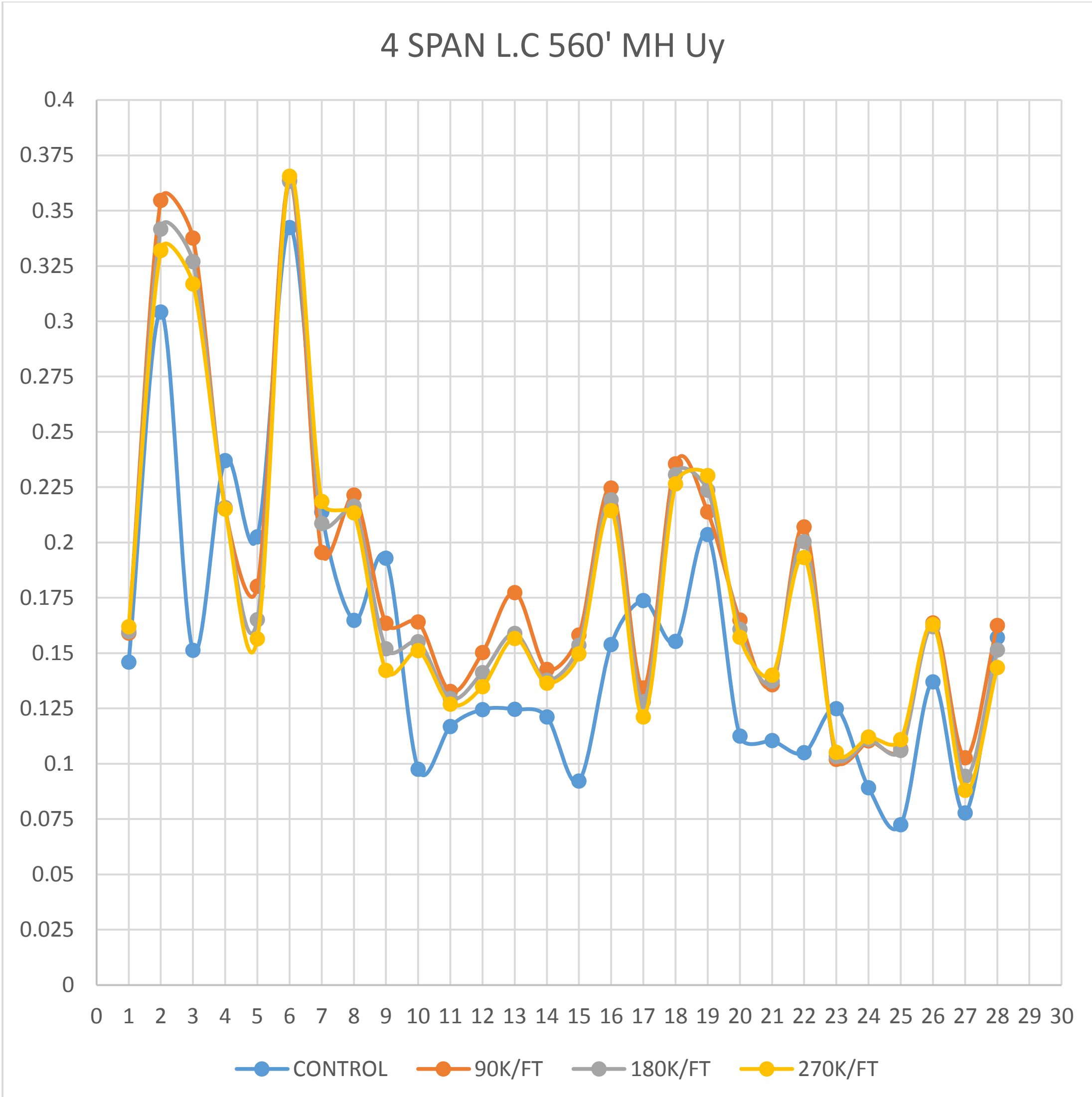


Fig. 3-116 Variation of transverse displacement with isolator stiffness for medium to high intensity Near Field earthquakes, for the four span bridge.

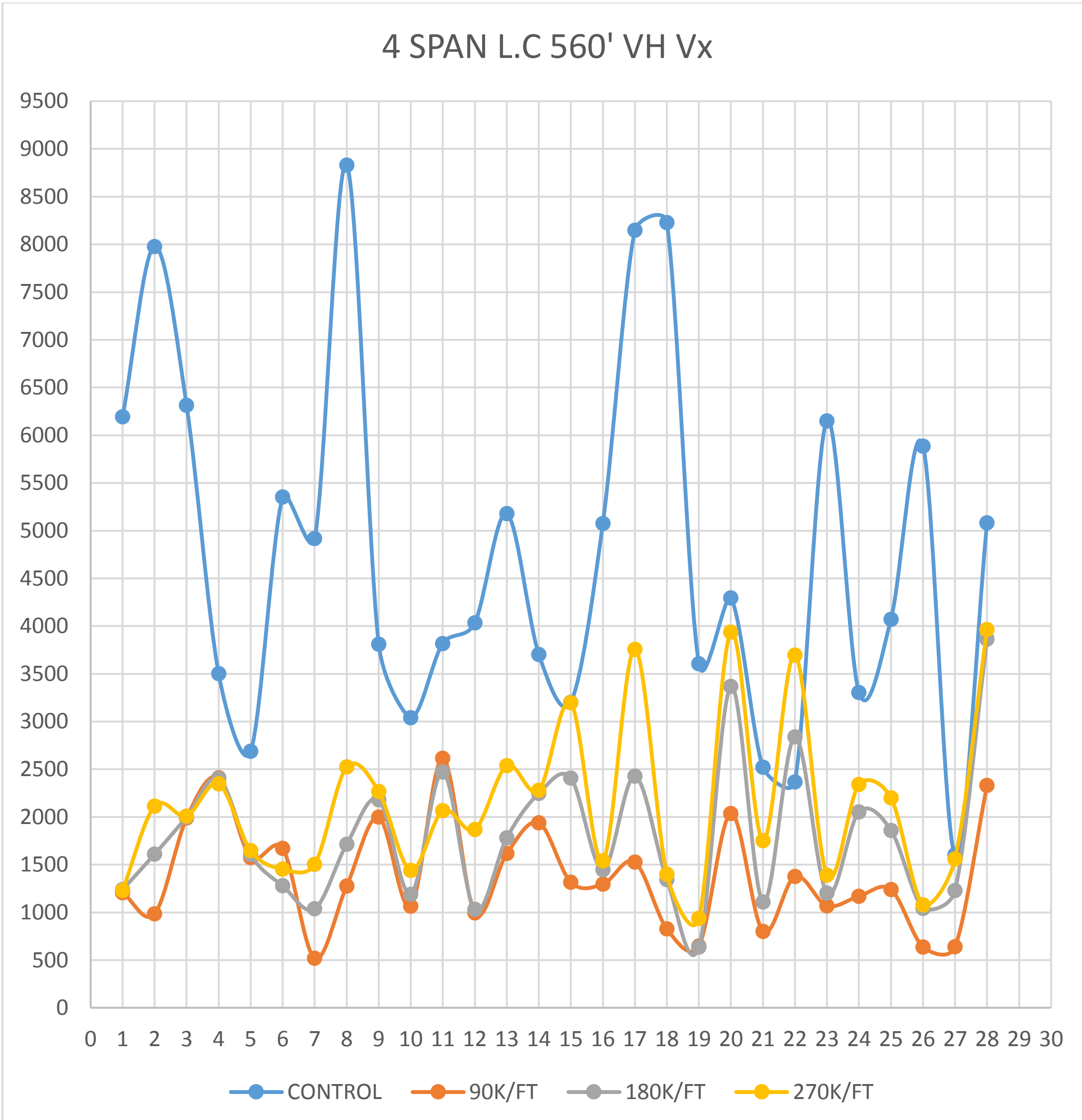


Fig. 3-117 Variation of longitudinal base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

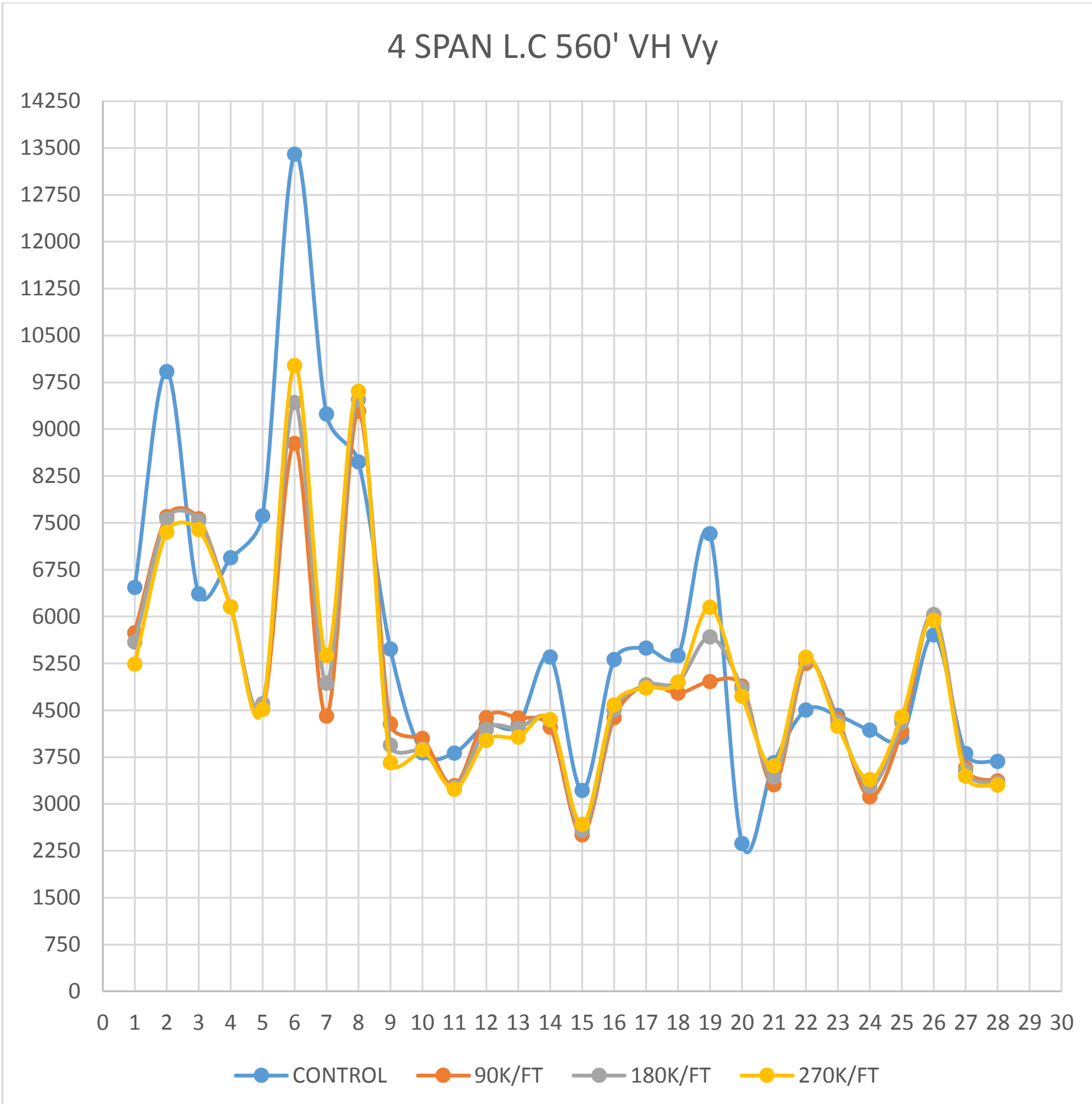


Fig. 3-118 Variation of transverse base shear with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

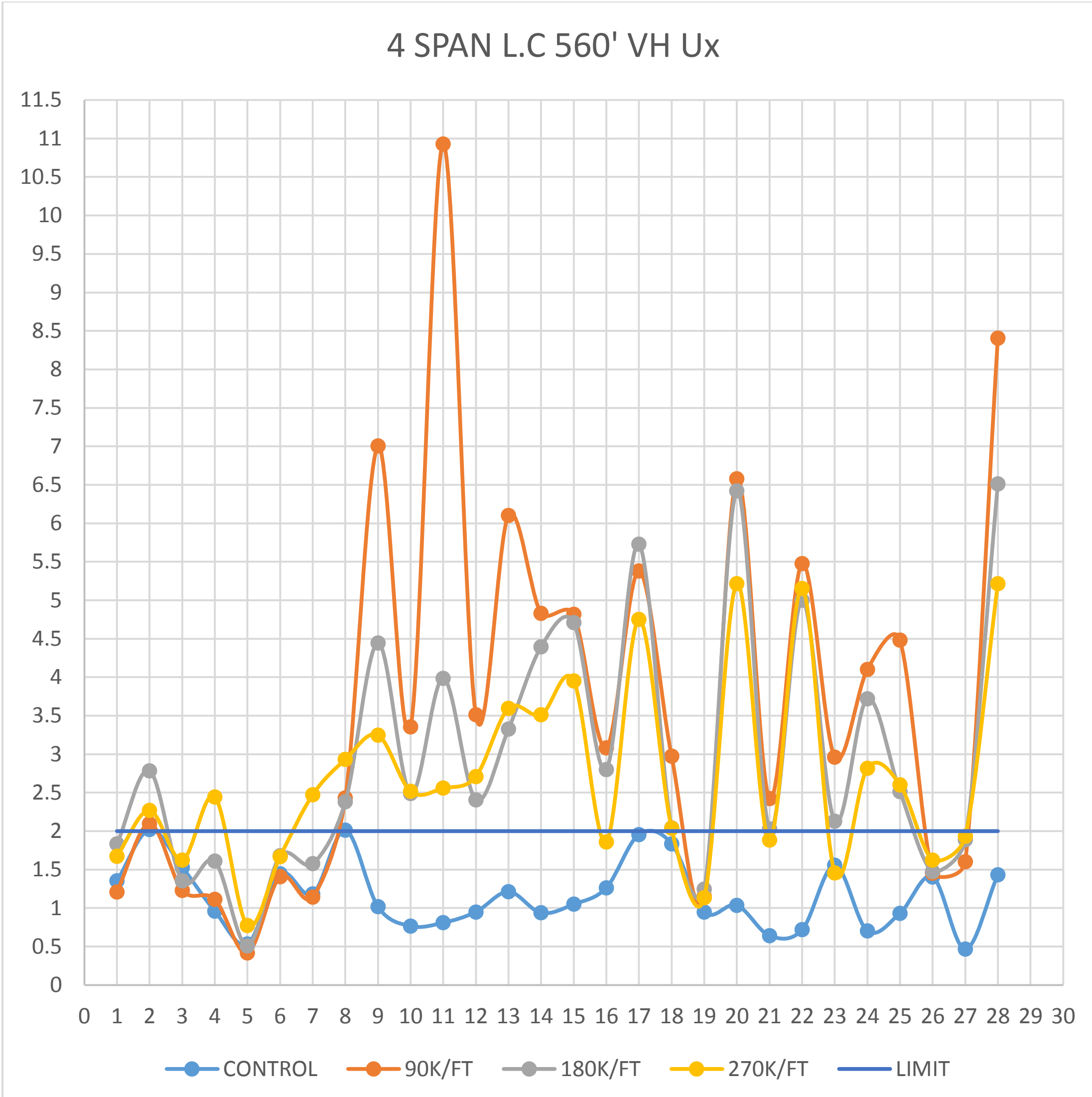


Fig. 3-119 Variation of longitudinal displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

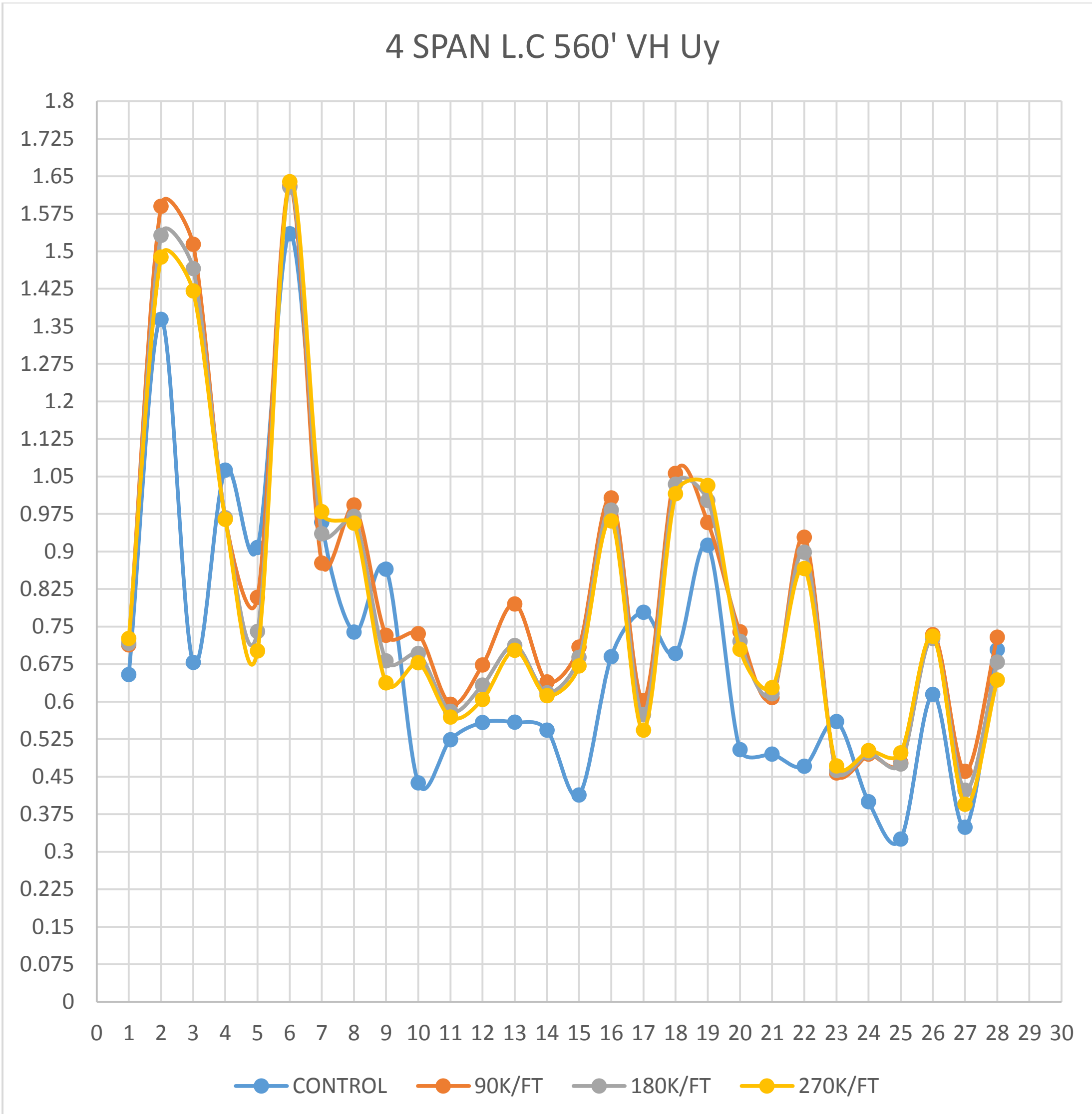


Fig. 3-120 Variation of transverse displacement with isolator stiffness for very high intensity Near Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded. See Fig. 3-121.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that all three stiffnesses can be used without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

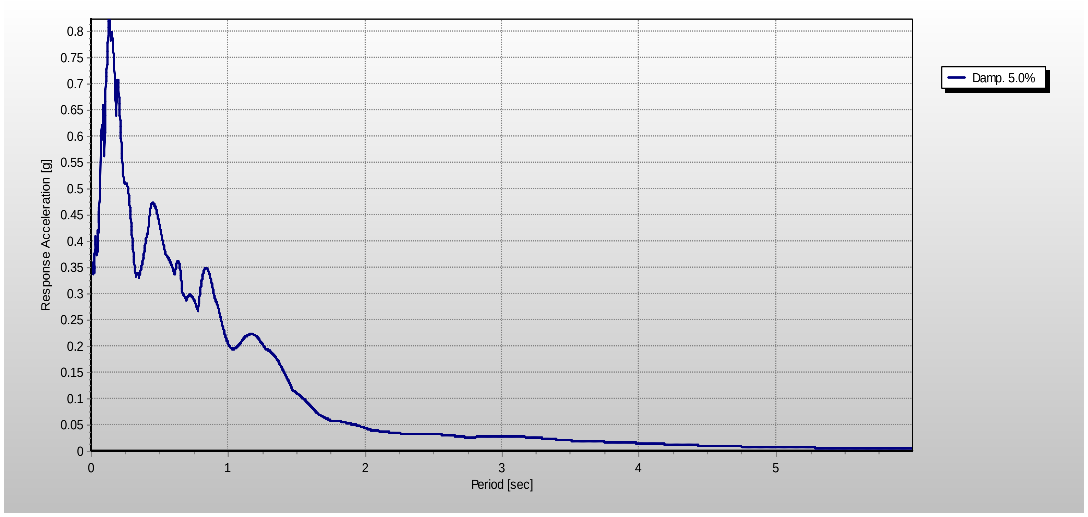


Fig. 3-121 Response curve of a typical Near Field Earthquake record.

The maximum longitudinal base shear values recorded for this case are:

Control = 8832.325

90 K/Ft = 2615.357

180 K/Ft = 3862.103

270 K/Ft = 3962.947

The results for the very high intensity near-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a

90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1493), showed that the maximum displacement recorded exceeded 4 feet and the maximum PGV value exceeded 6 ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

CHAPTER FOUR - RESULTS AND DISCUSSIONS OF ISOLATOR RESPONSE TO FAR FIELD EARTHQUAKE GROUND MOTIONS

The results shown in this chapter include plots of response quantities for various parameters when subjected to far field earthquake ground motions. Table 4-1 shows the list of the far field ground motions used. The table shows the NGA record sequence numbers and the earthquake names. The parameters include the isolator stiffness, high intensity scaled earthquakes(H), medium to high intensity earthquakes(MH), very high intensity earthquakes(VH). The response quantities include the following: Longitudinal Displacement (Ux), Transverse Displacement (Uy), Longitudinal Base Shear (Vx), Transverse Base Shear (Vy), and period of vibration. The vertical axis represents the base shear or the displacement values. The horizontal axis represents the NGA record sequence number. The units used for displacement values is feet, the units used for base shear is kips, and the units used for stiffness values is kips per feet. The nodes which had the maximum values of longitudinal and transverse displacements were used to generate the displacement curves. The Control case represents the case where no isolators are provided.

Table 4-1 List of far field earthquakes

No.	NGA record sequence number
1	1116-FN
2	1116-FP
3	125-FN
4	125-FP
5	827-FN
6	827-FP
7	1158-FN
8	1158-FP
9	1246-FN
10	1246-FP
11	1602-FN
12	1602-FP
13	169-FN
14	169-FP
15	1787-FN
16	1787-FP
17	752-FN
18	752-FP
19	864-FN
20	864-FP
21	960-FN
22	960-FP

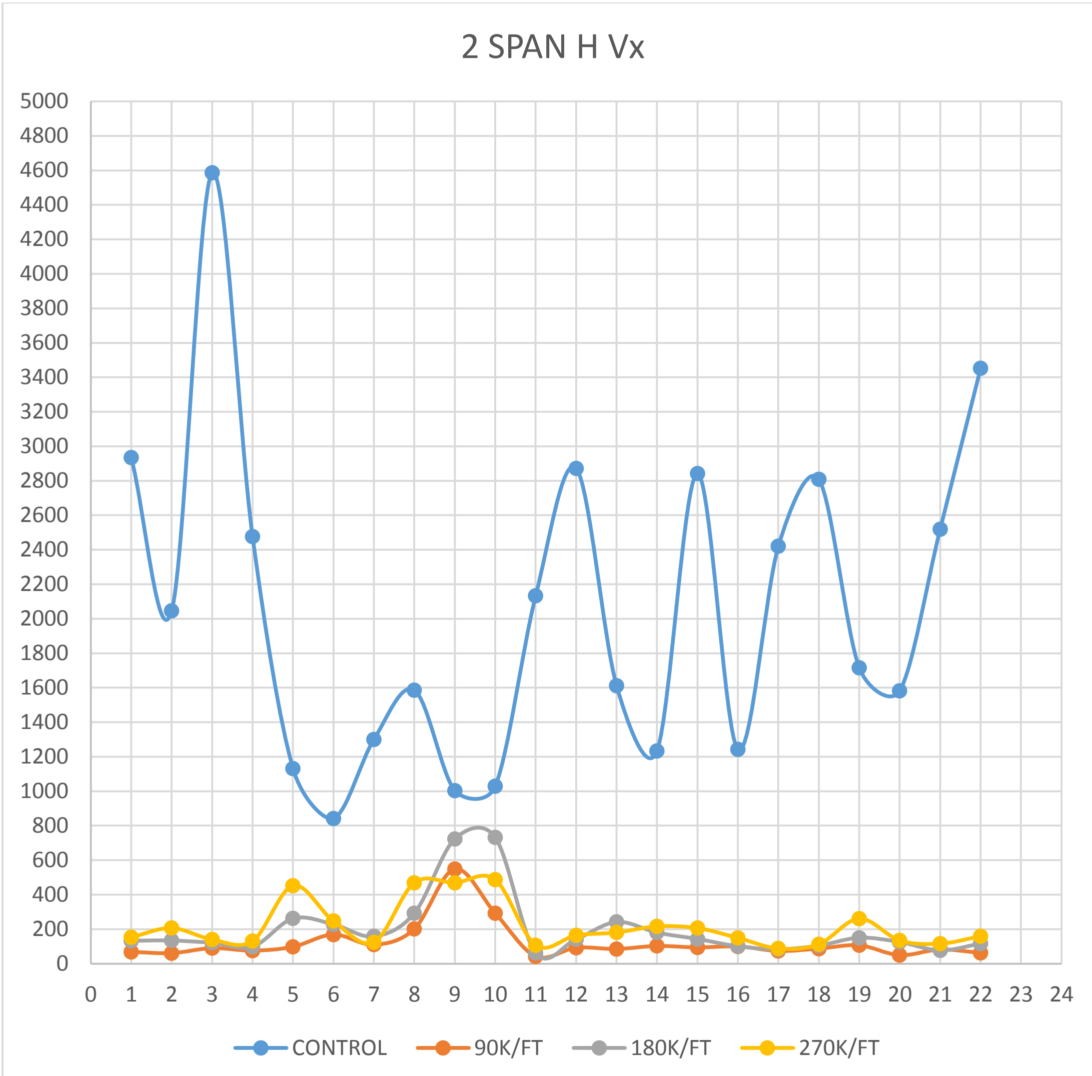


Fig. 4-1 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

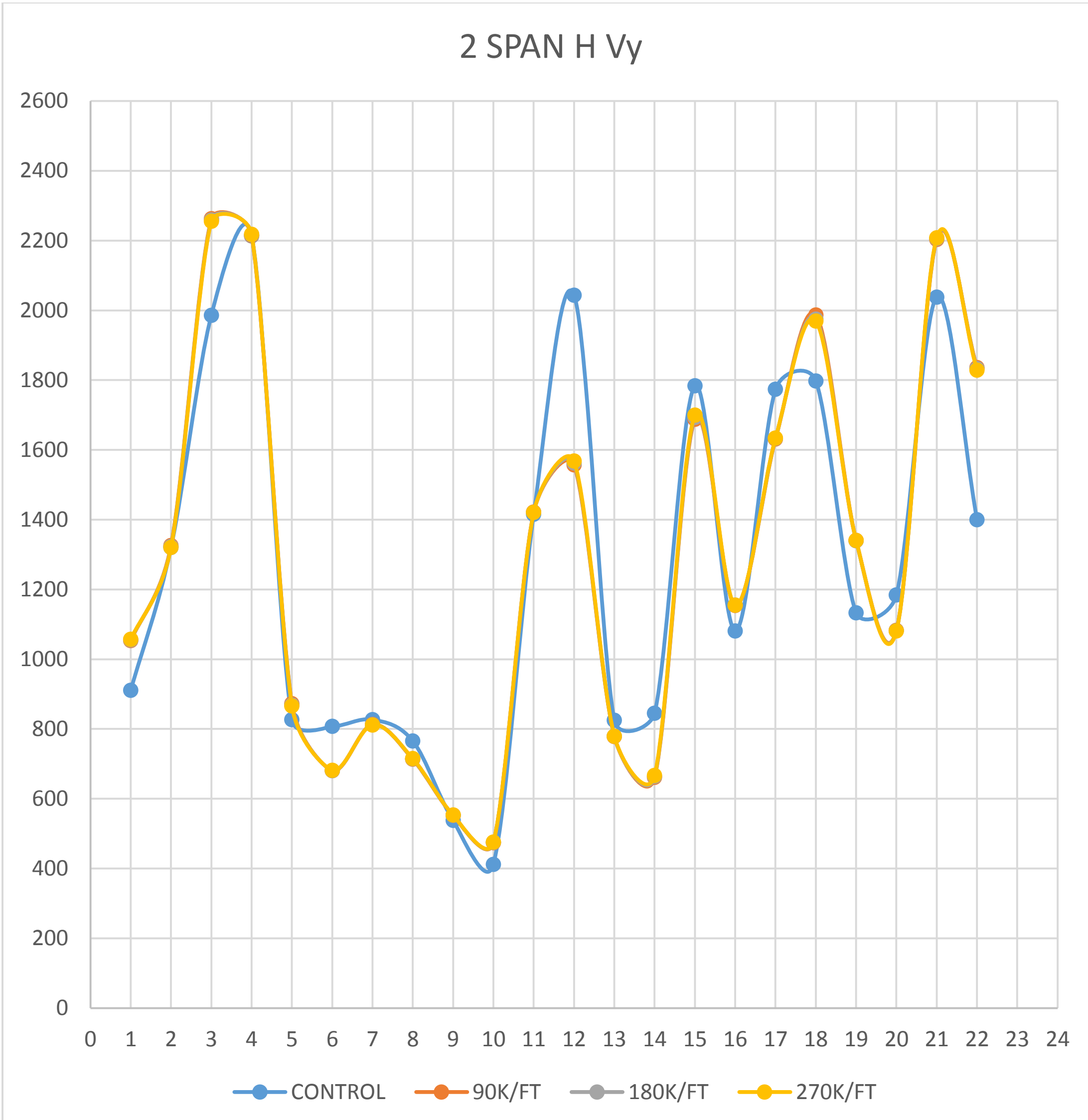


Fig. 4-2 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

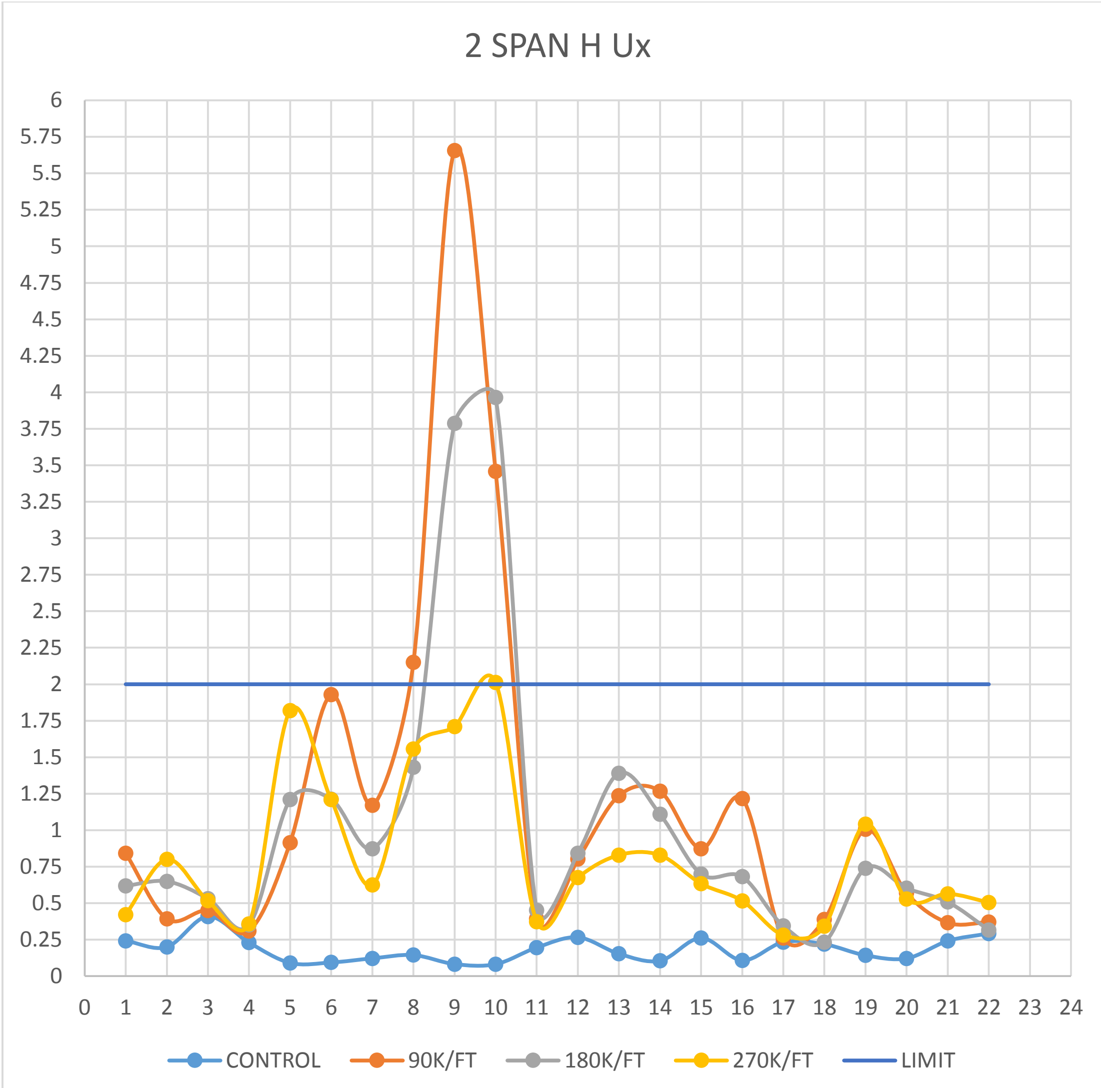


Fig. 4-3 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

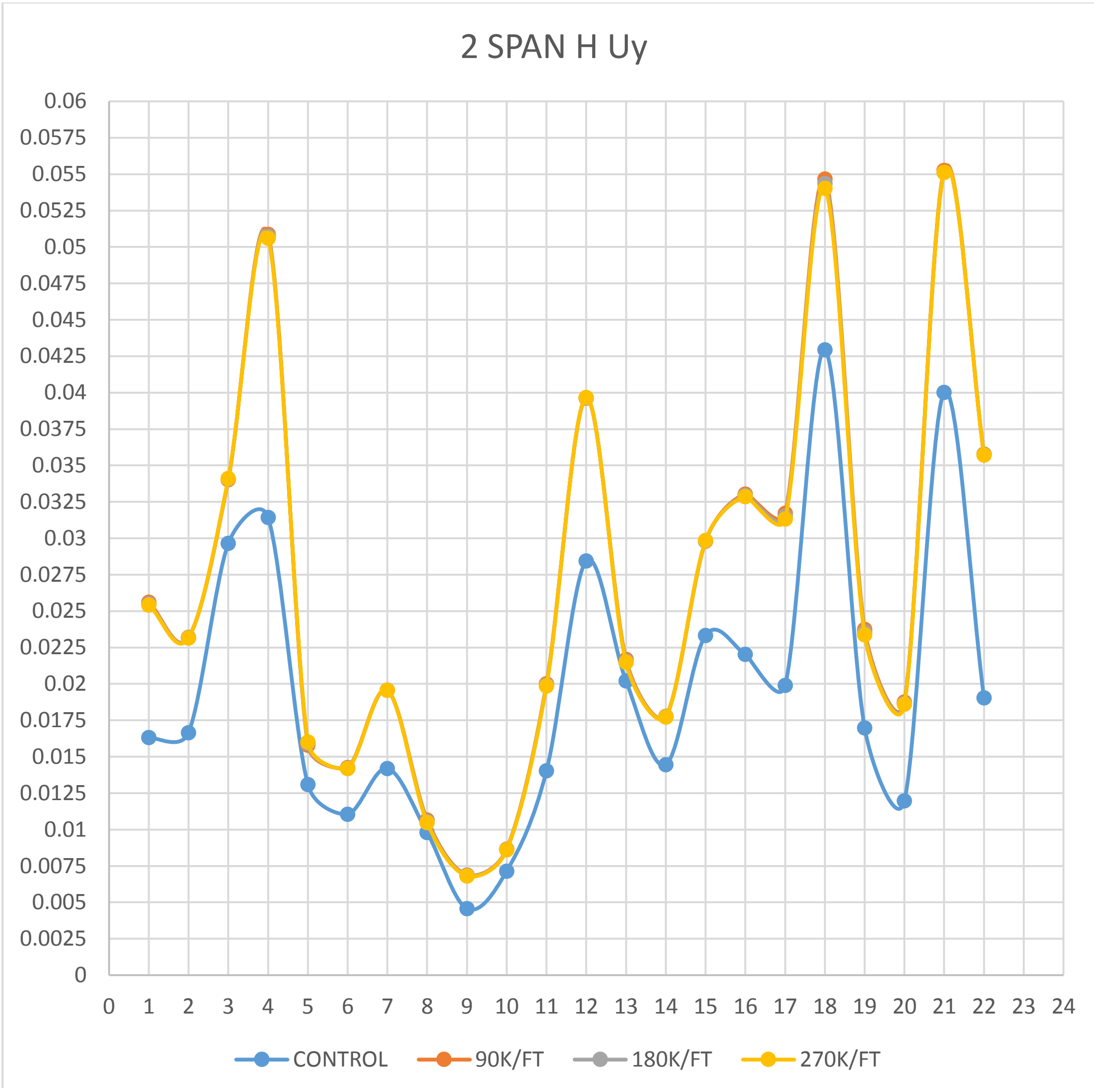


Fig. 4-4 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

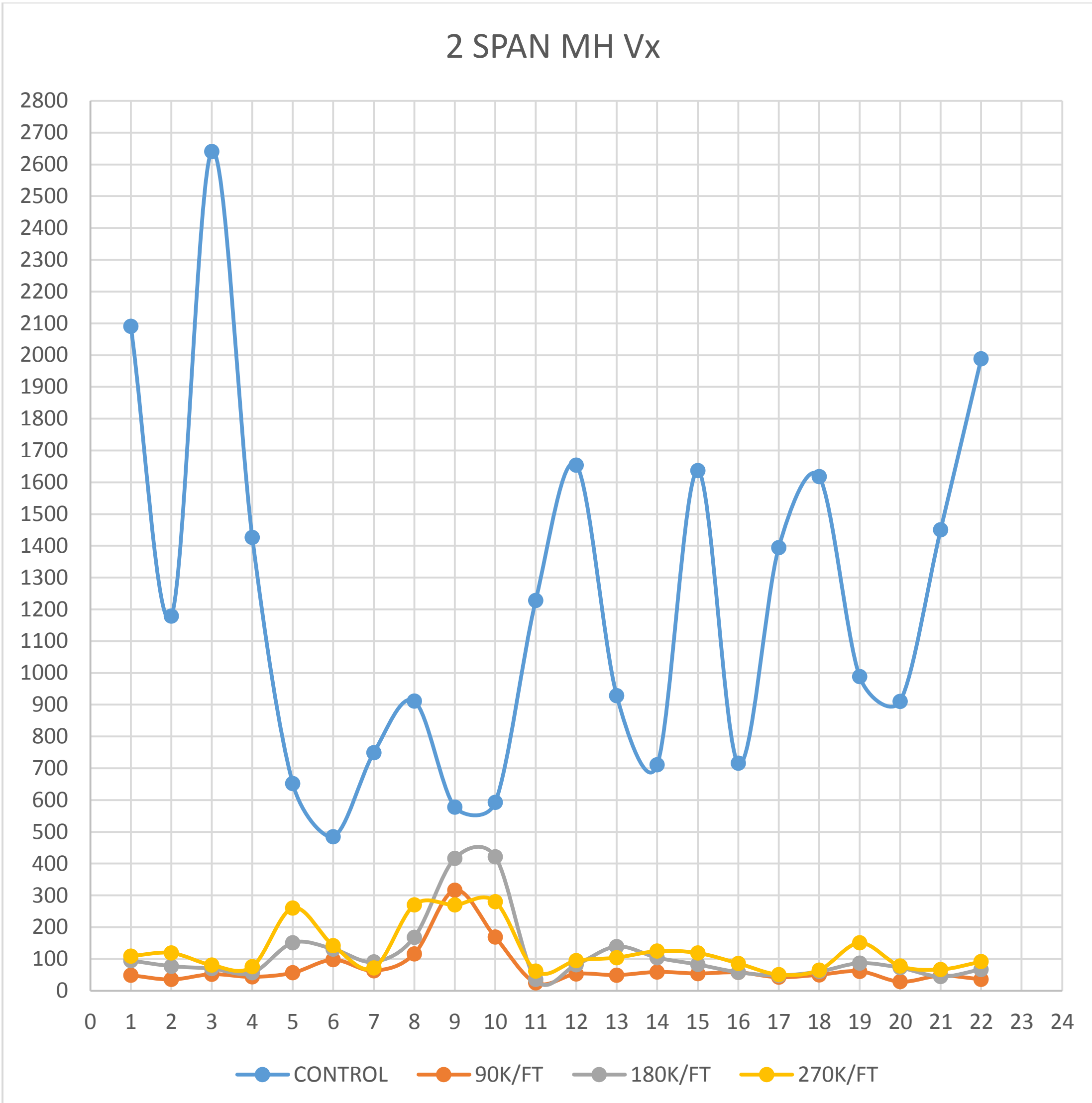


Fig. 4-5 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

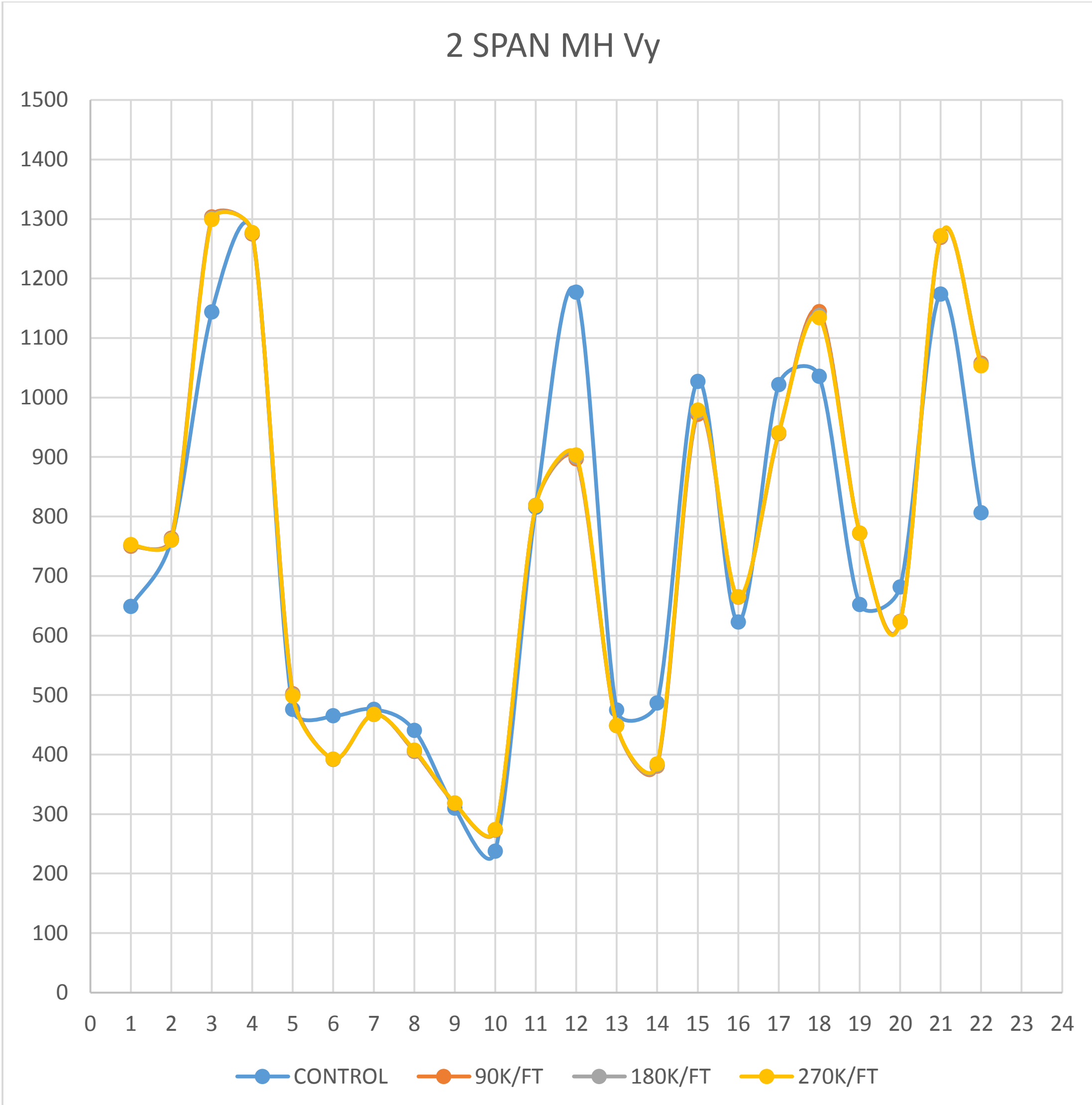


Fig. 4-6 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

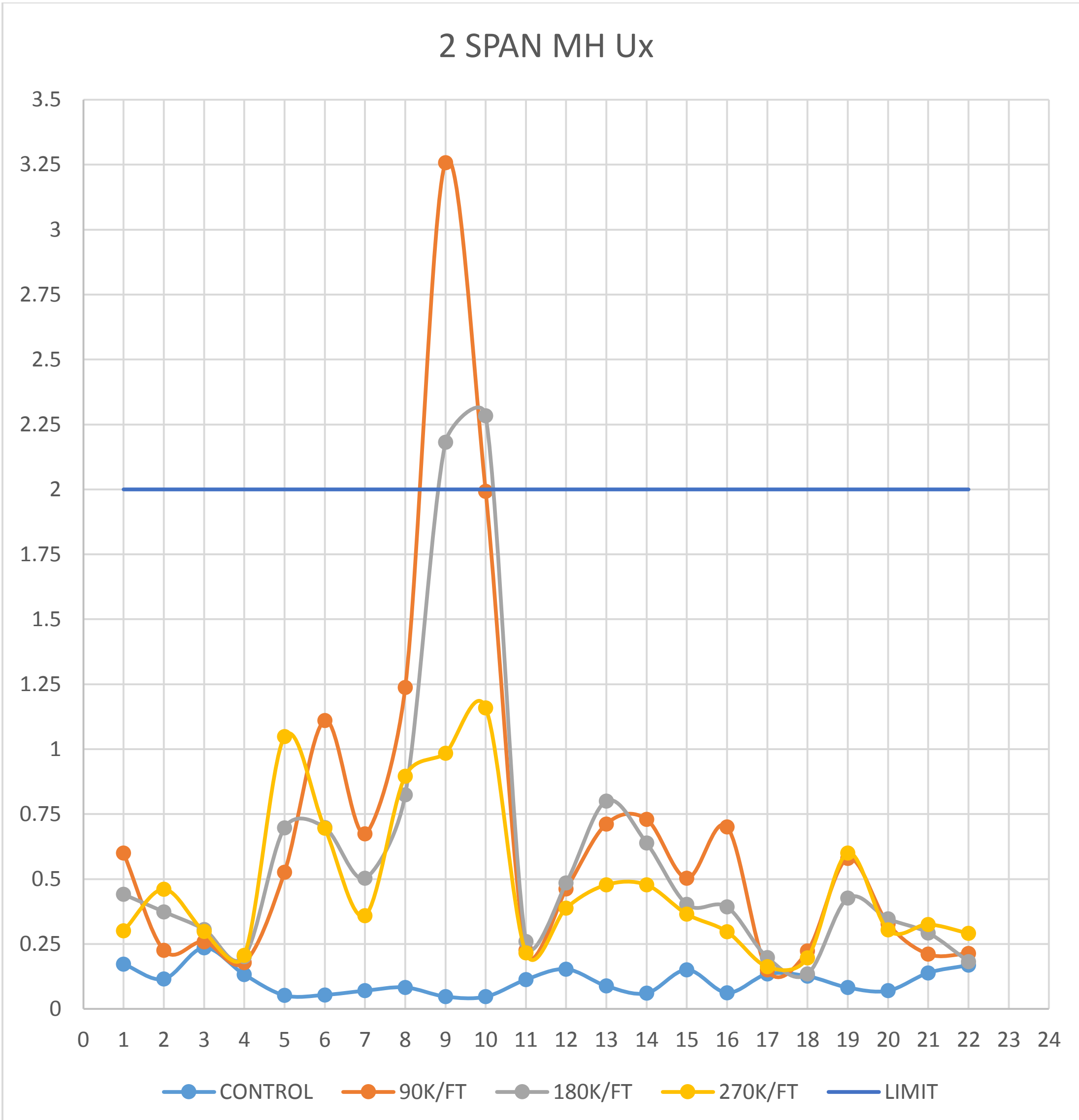


Fig. 4-7 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

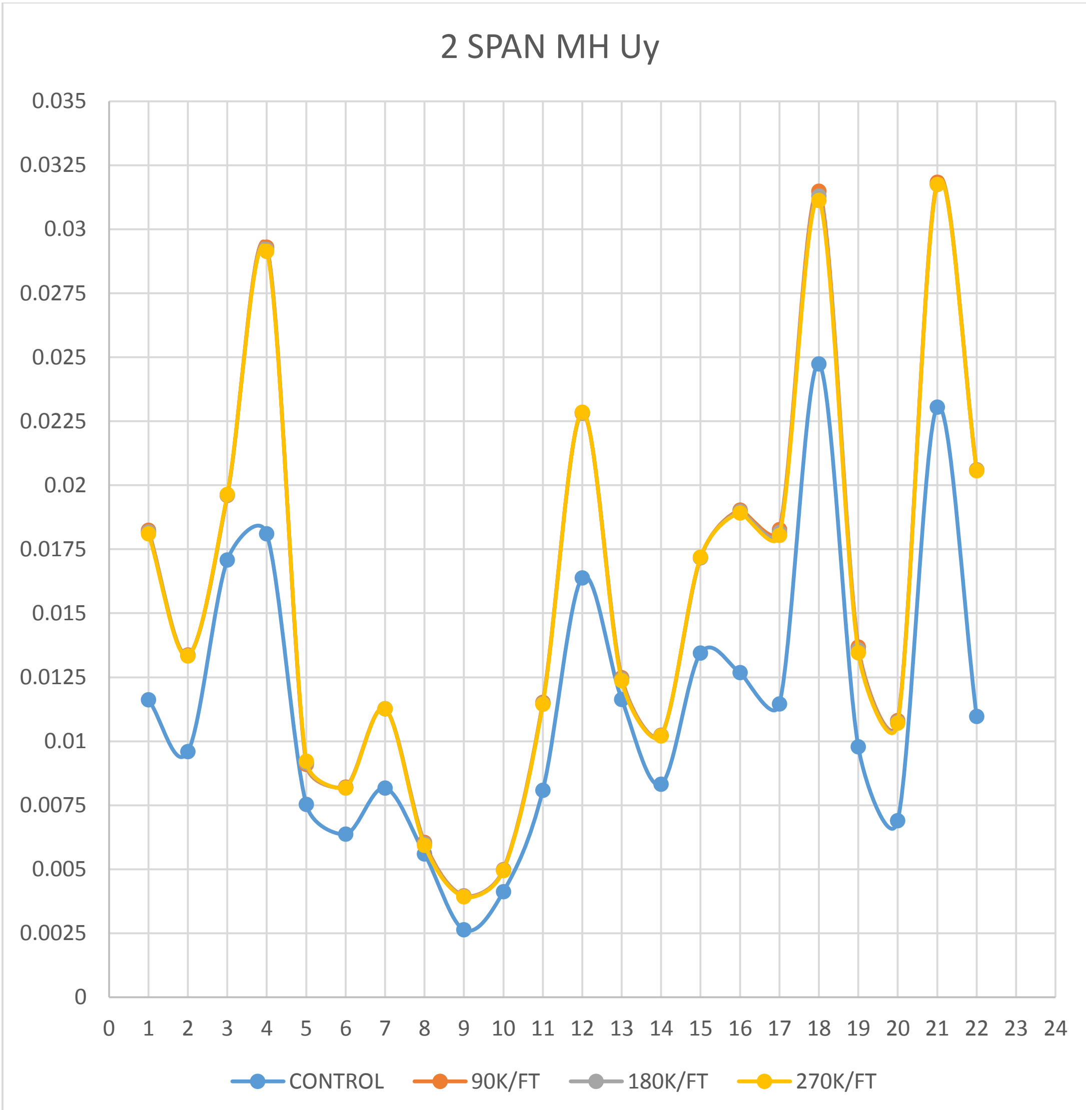


Fig. 4-8 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

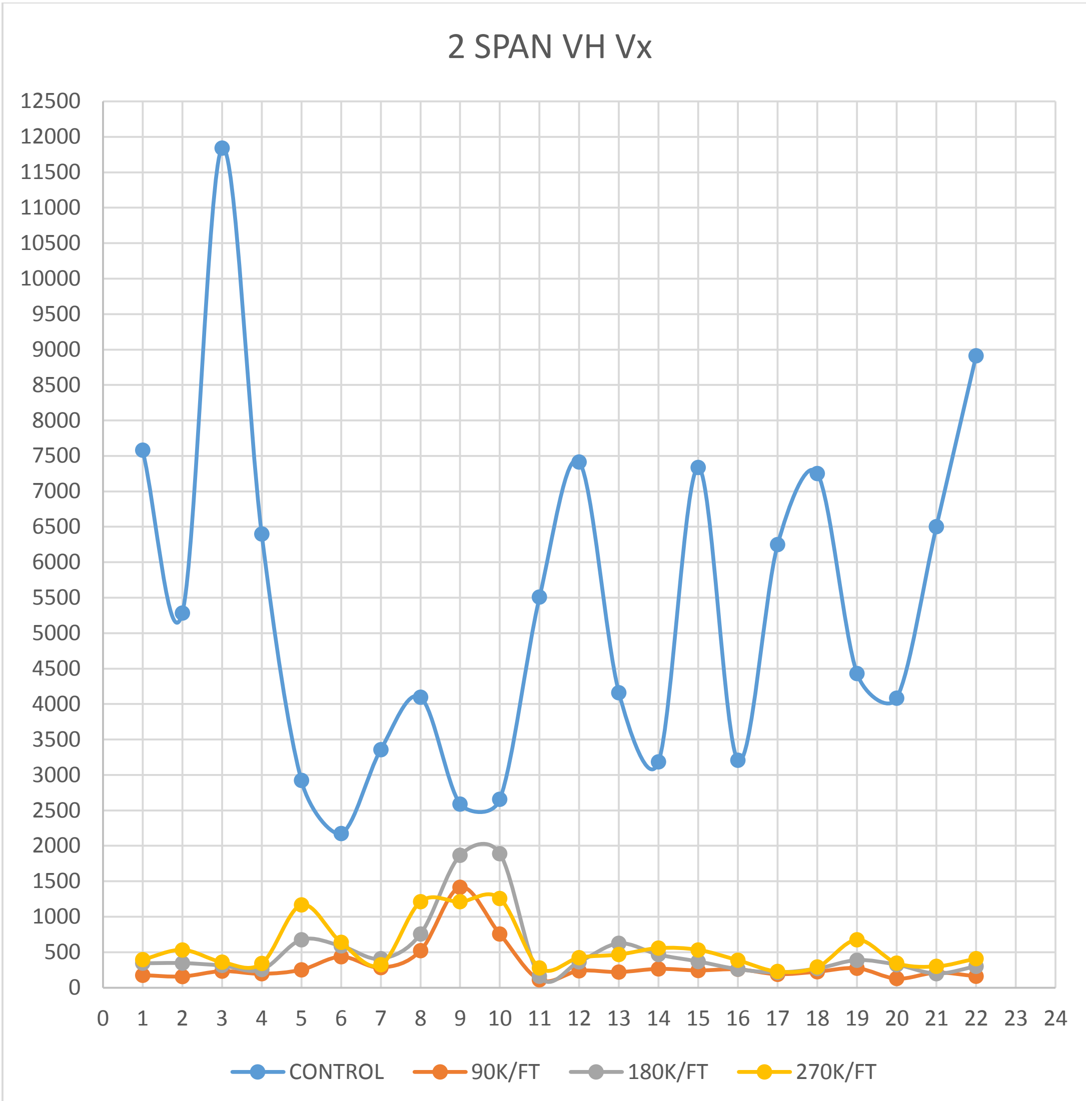


Fig. 4-9 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

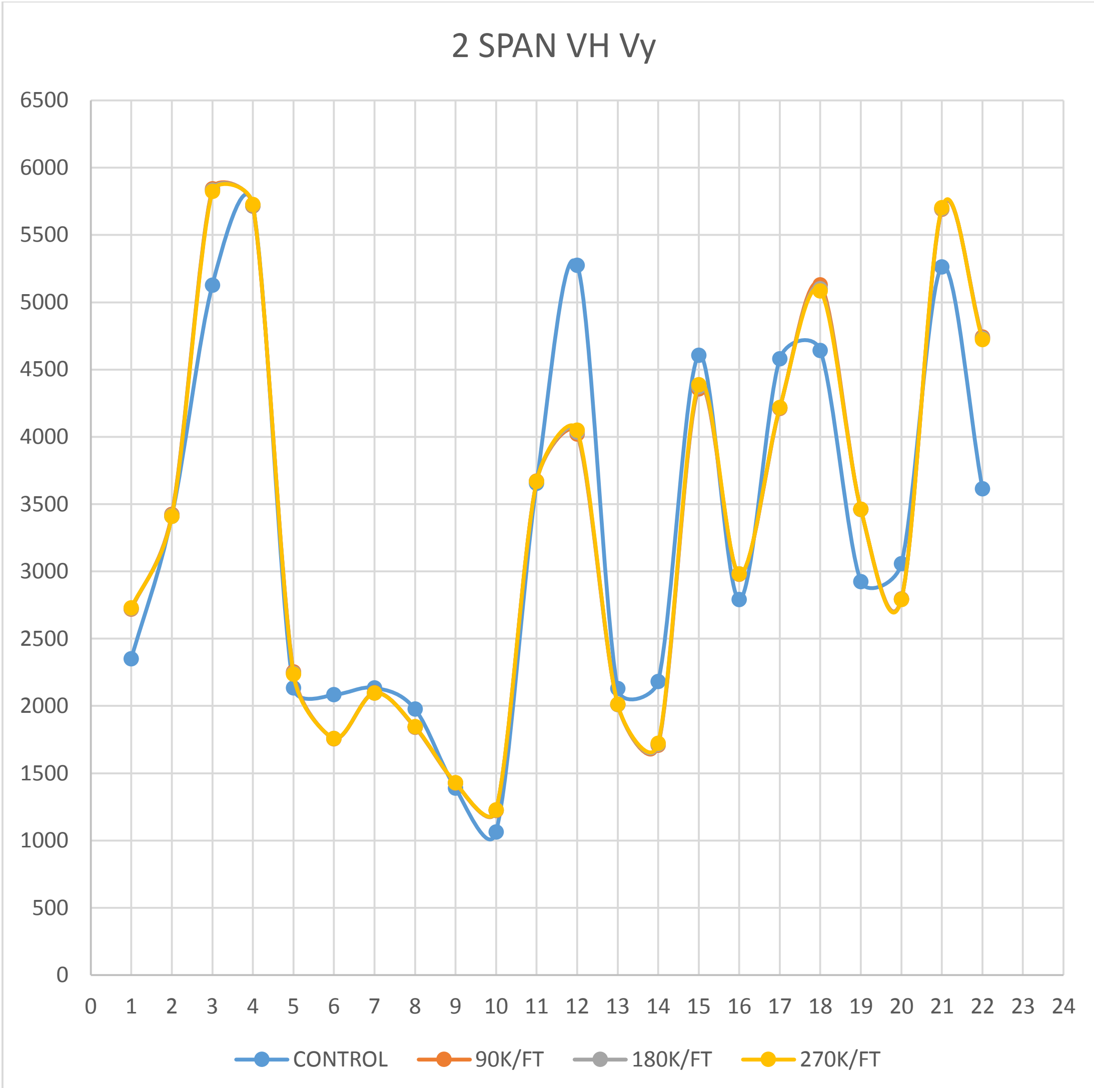


Fig. 4-10 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

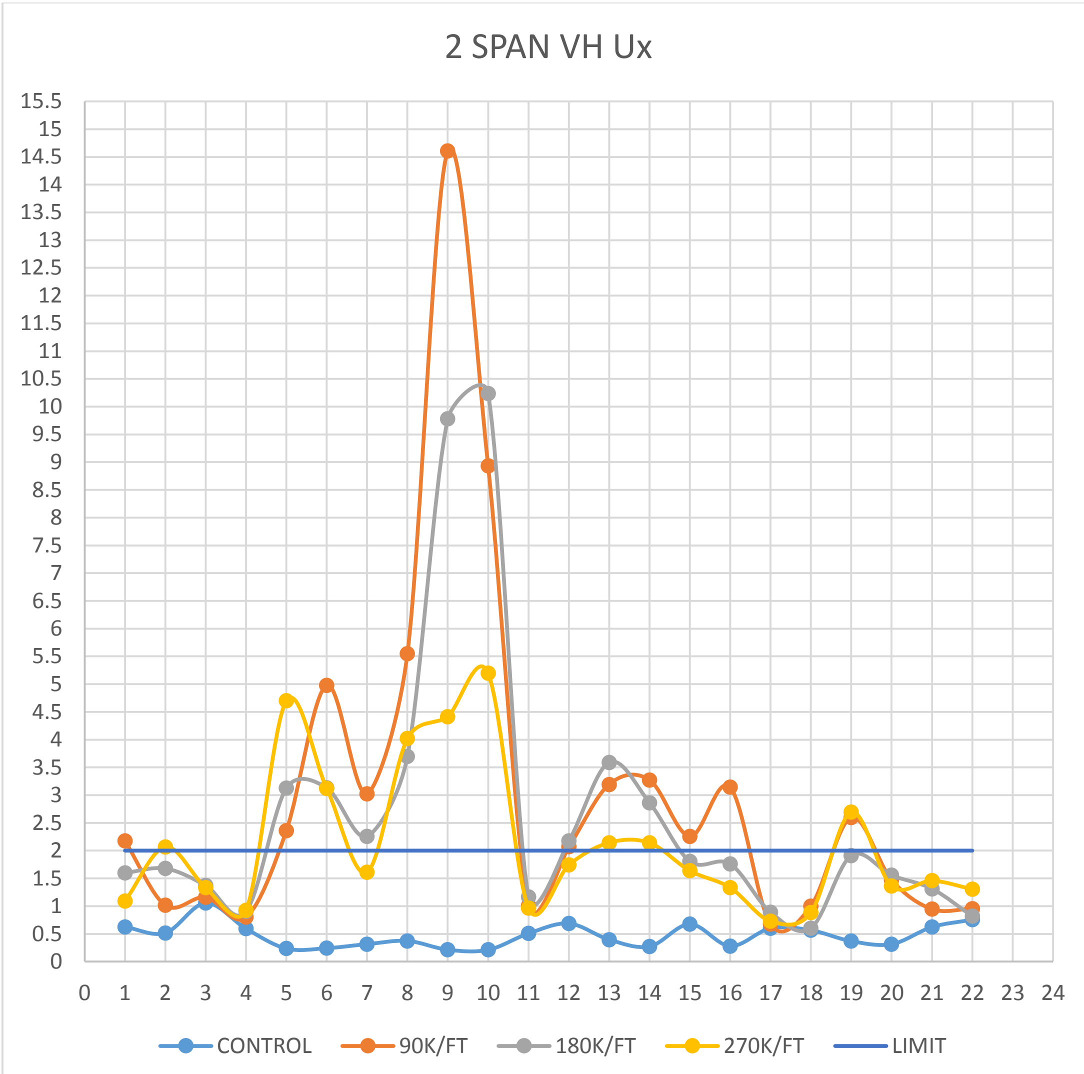


Fig. 4-11 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

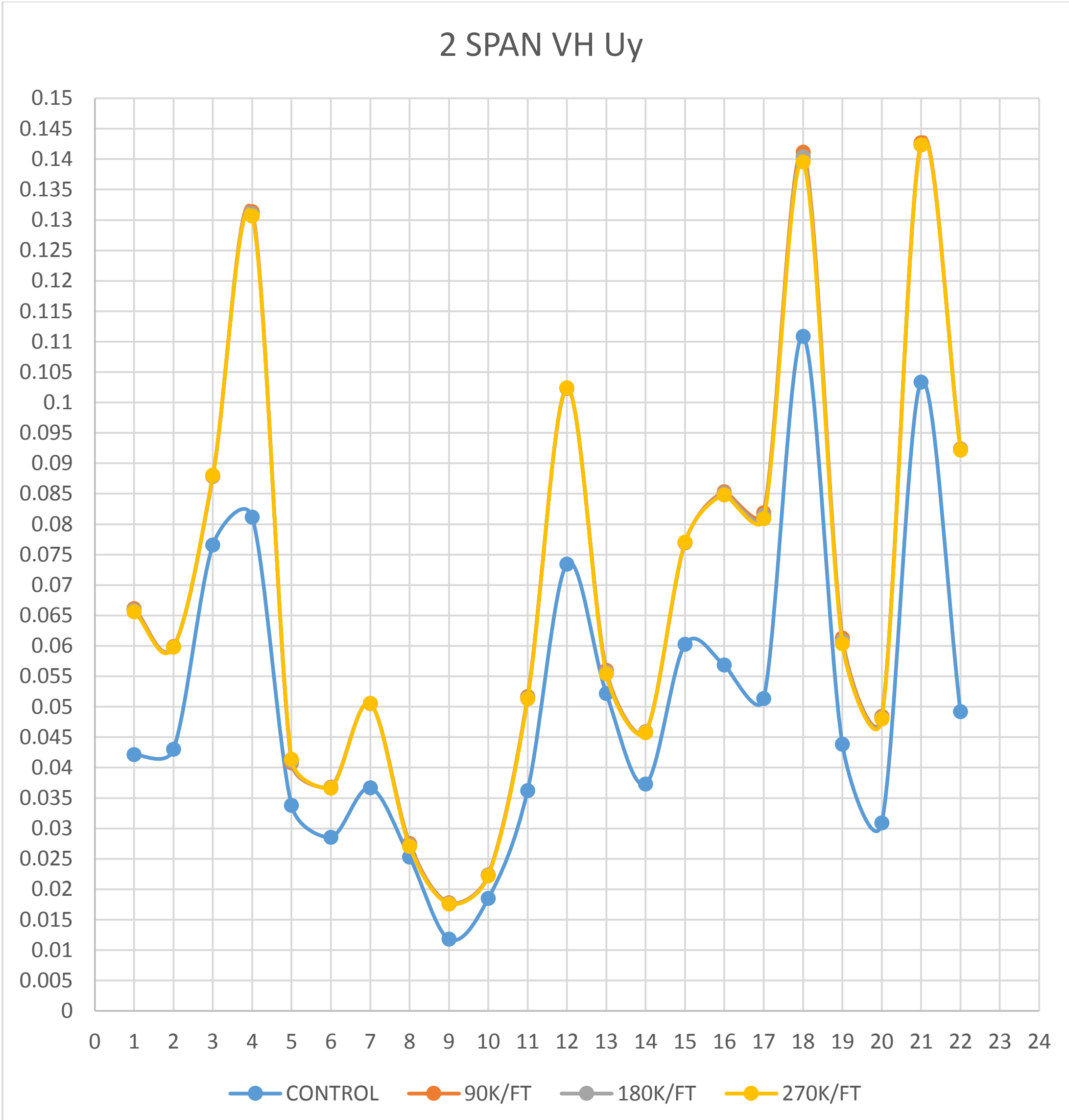


Fig. 4-12 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 2 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 2 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 2 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 11840.79

90 K/Ft = 1417.274

180 K/Ft = 1890.355

270 K/Ft = 1256.482

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

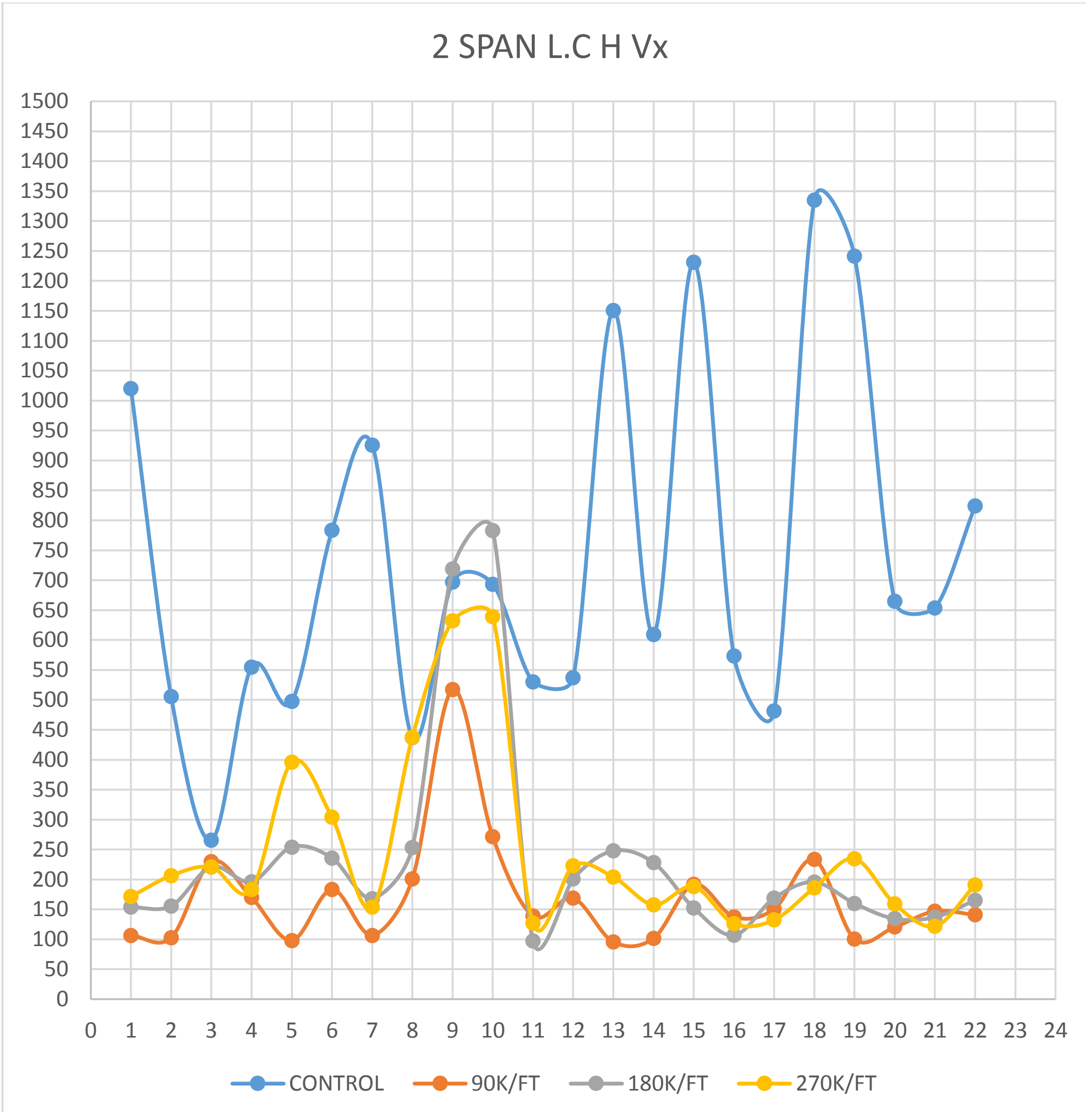


Fig. 4-13 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

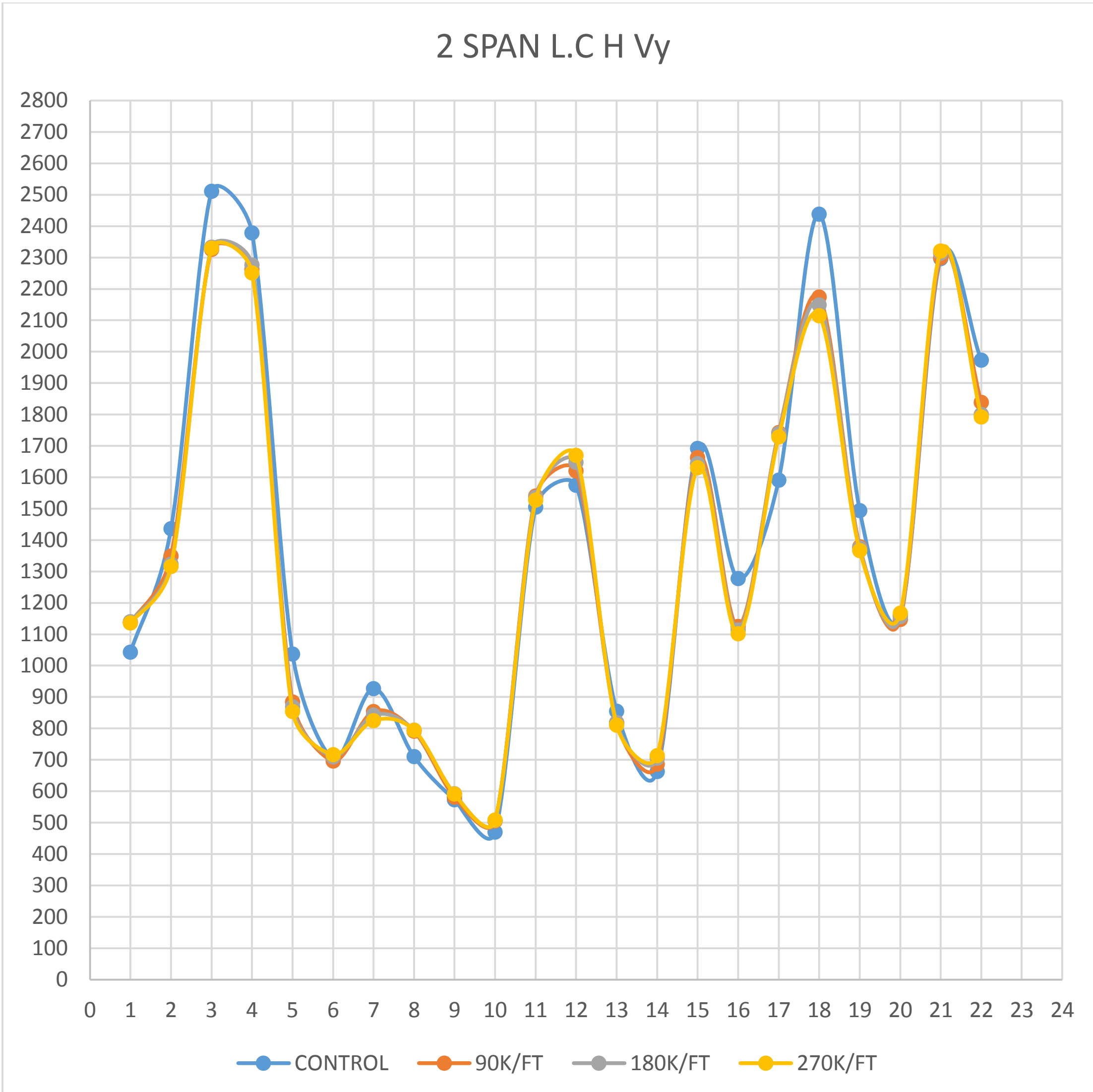


Fig. 4-14 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

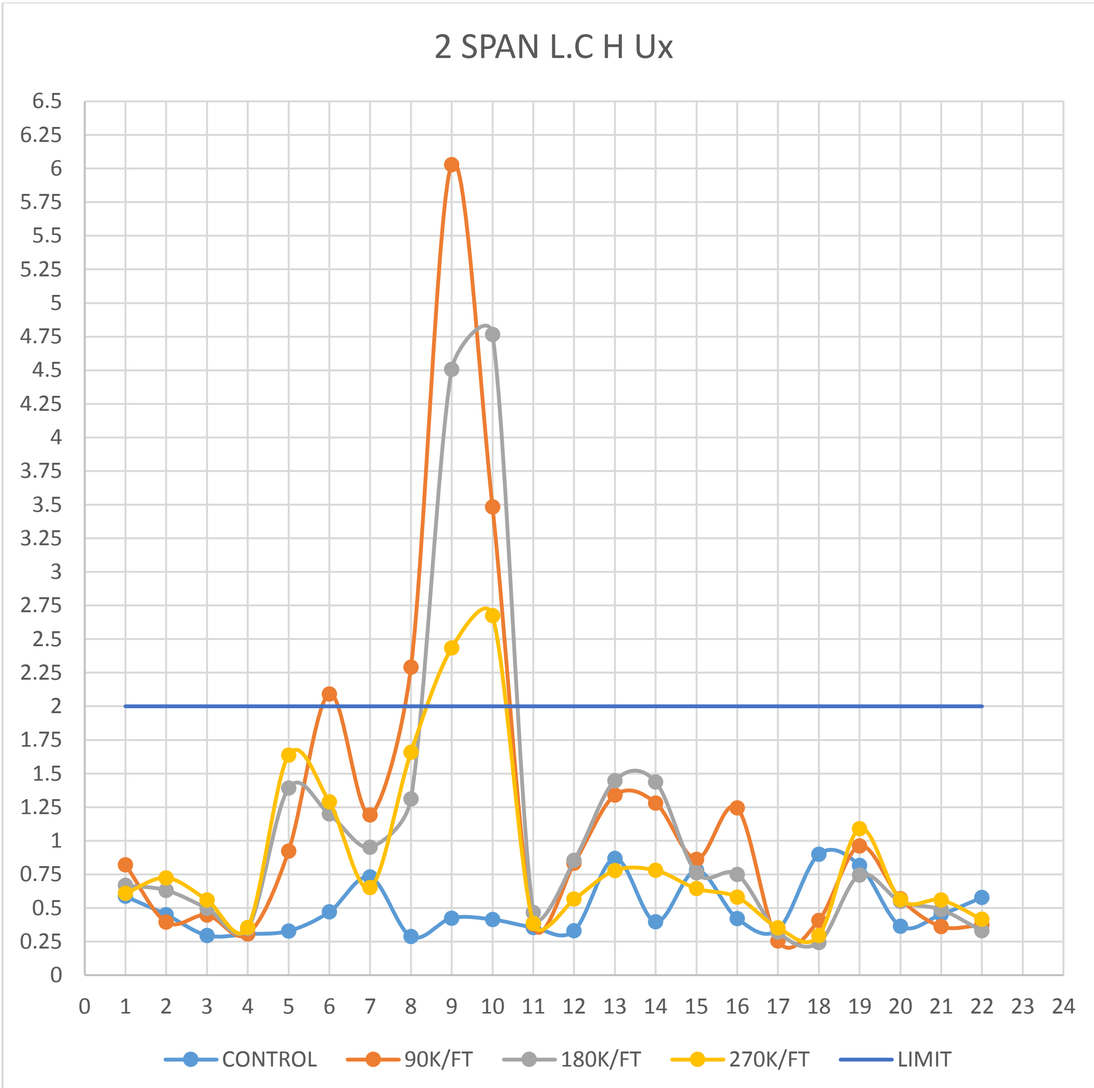


Fig. 4-15 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

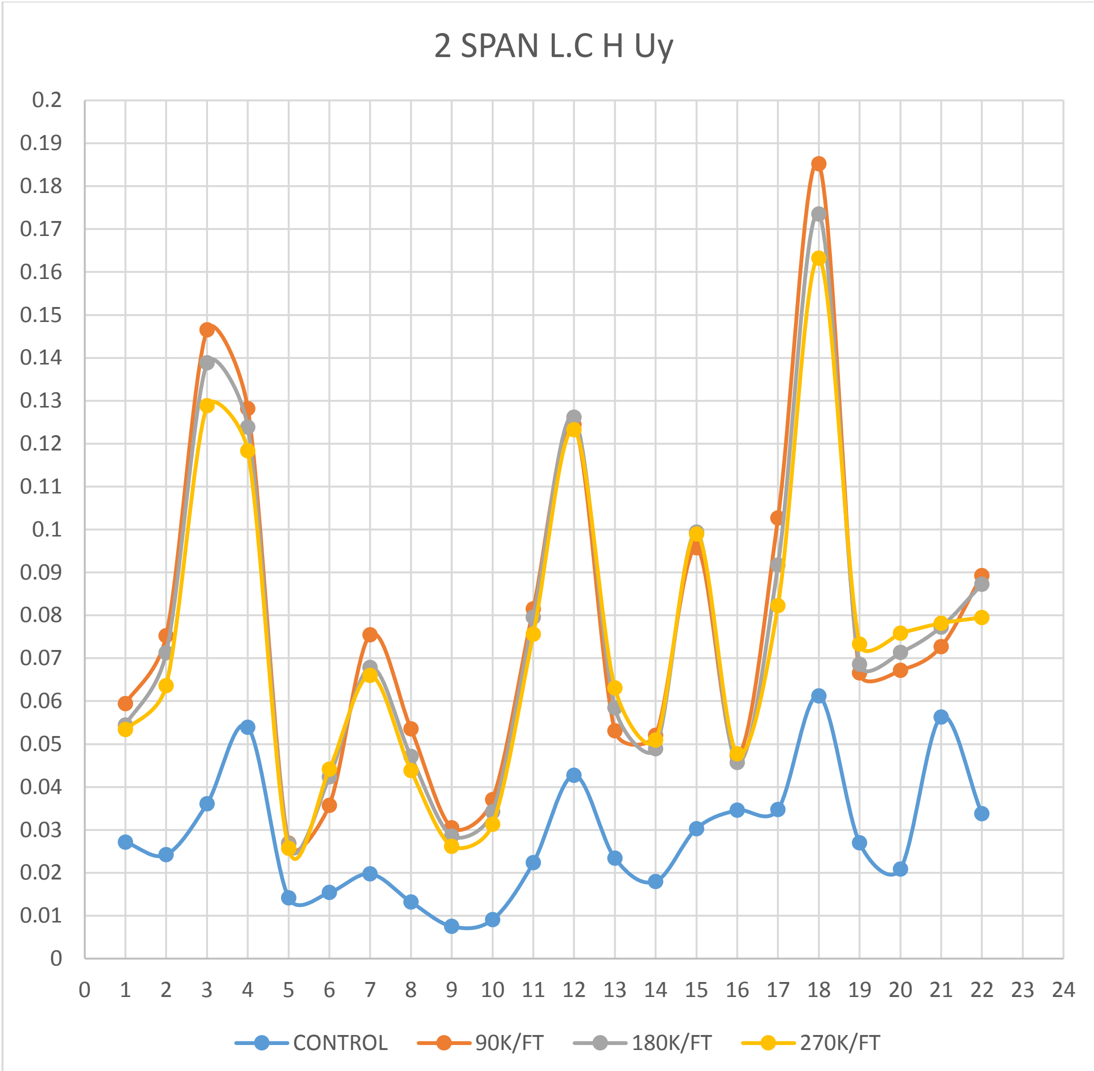


Fig. 4-16 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the two span bridge.

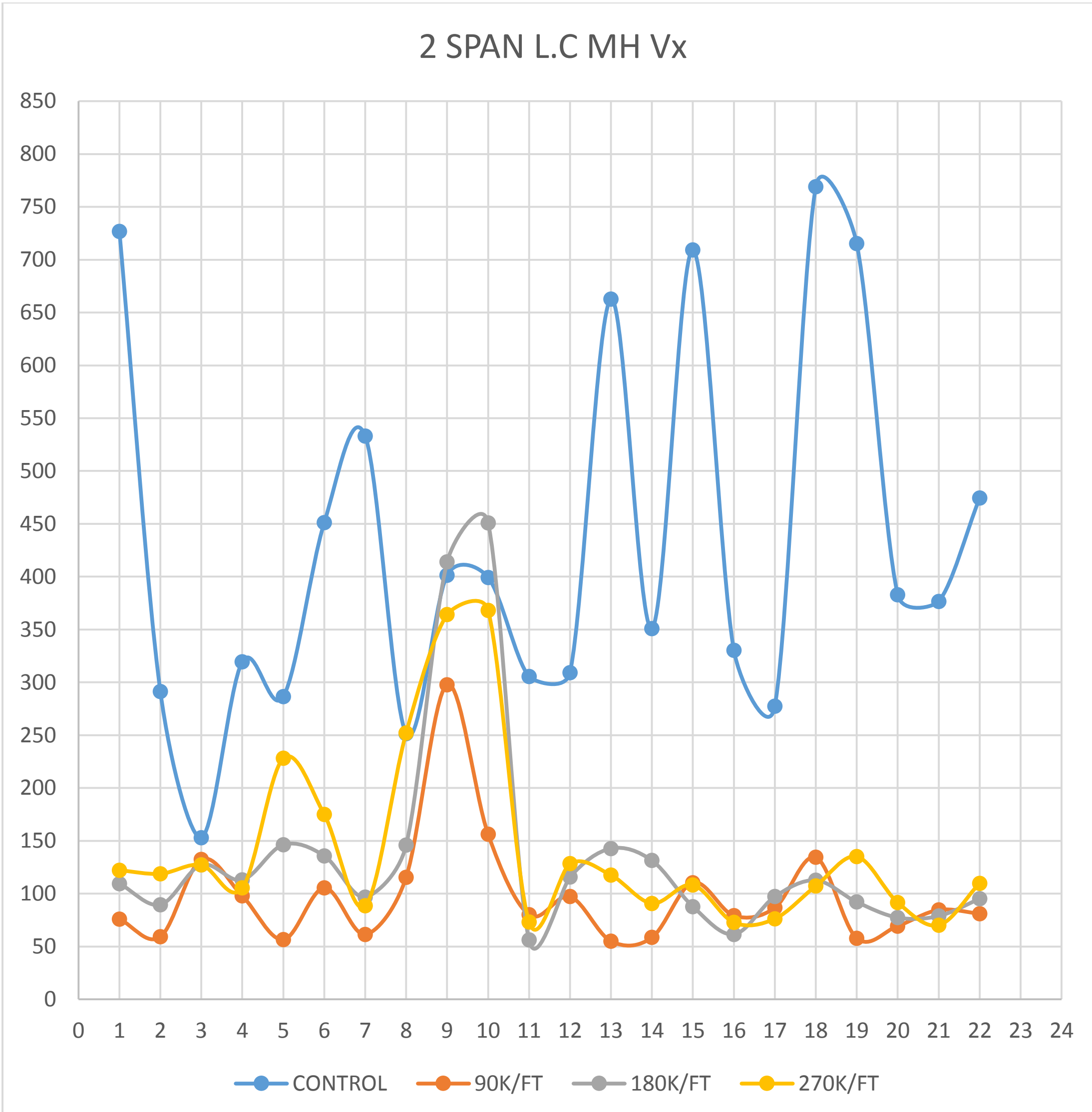


Fig. 4-17 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

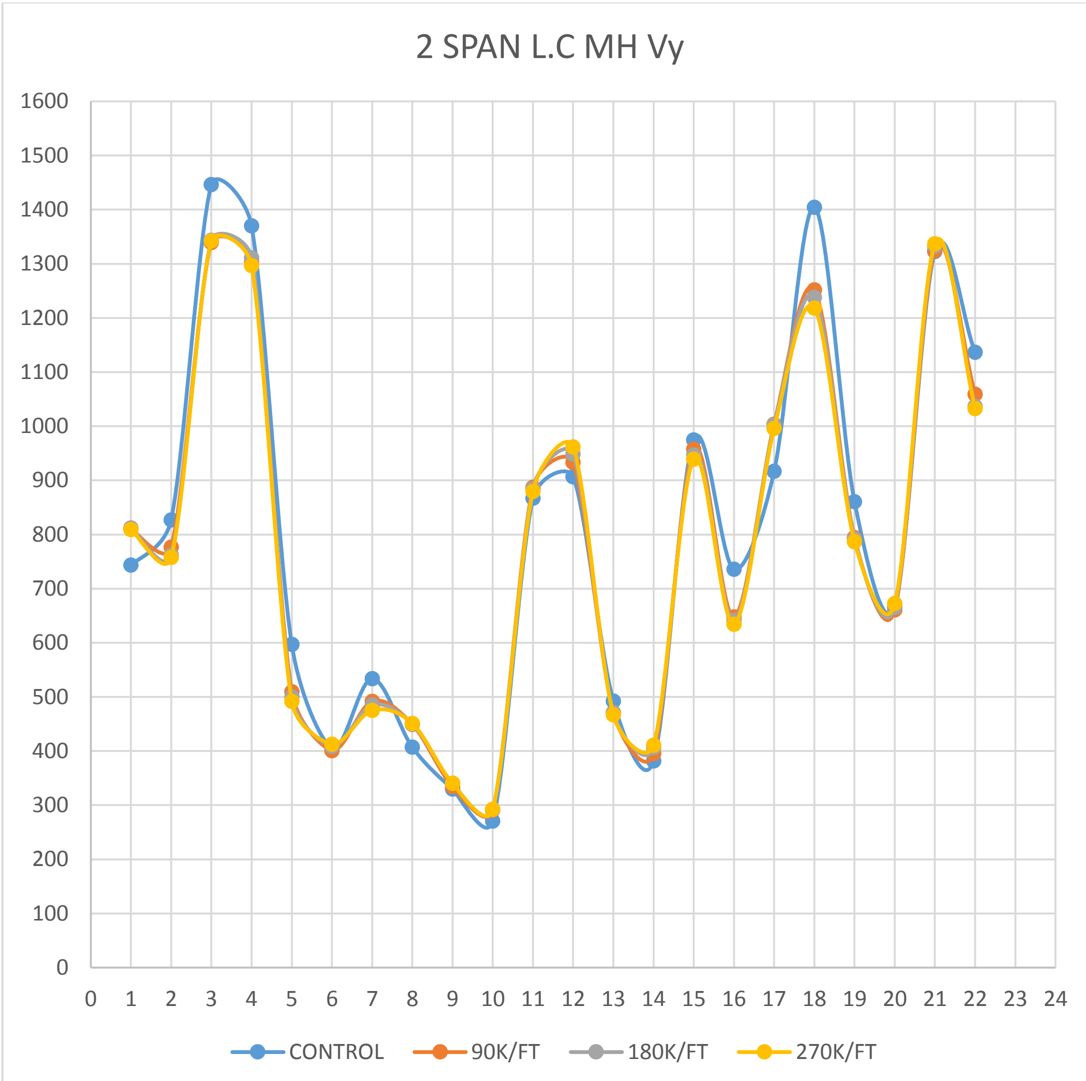


Fig. 4-18 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

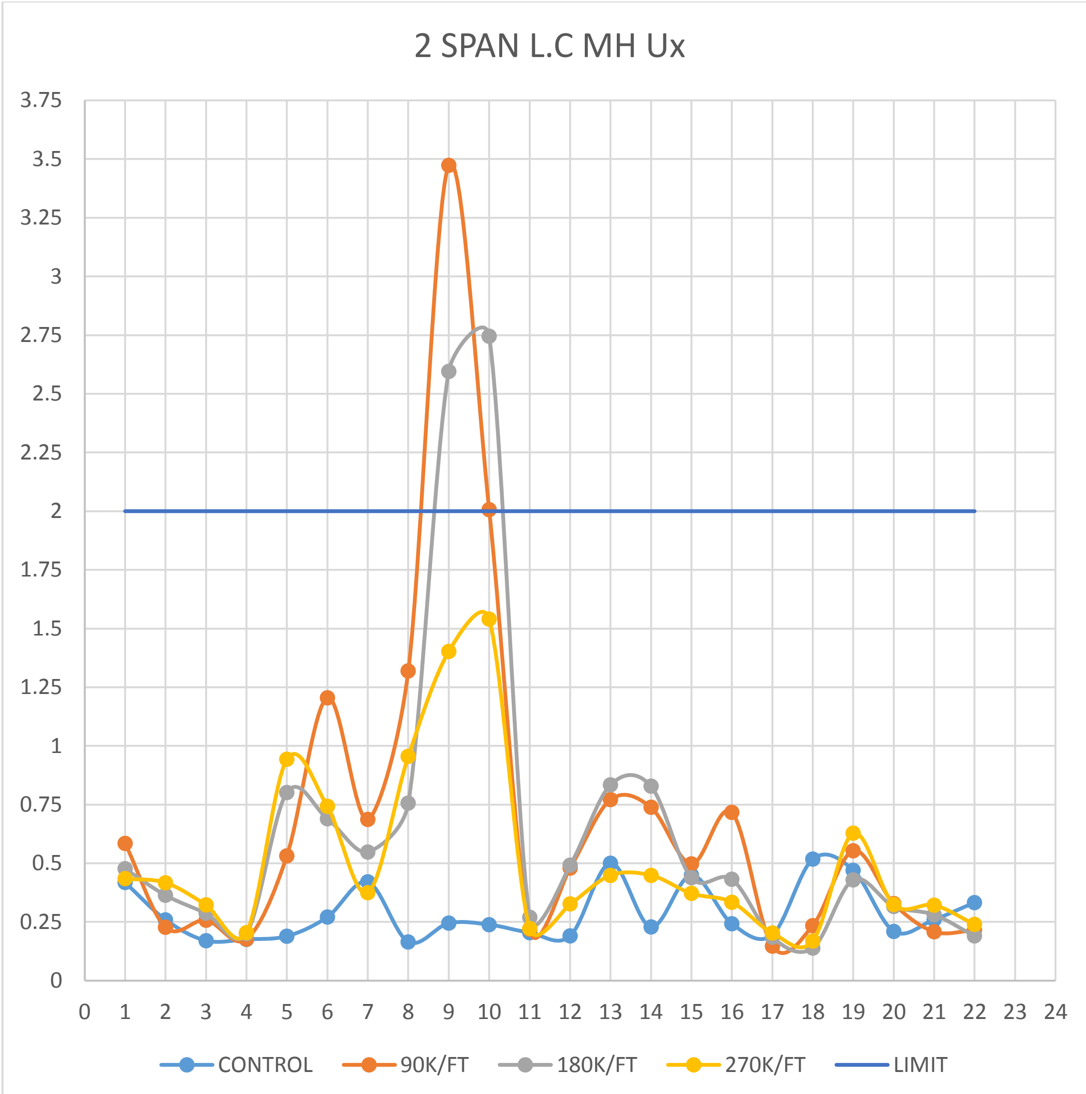


Fig. 4-19 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

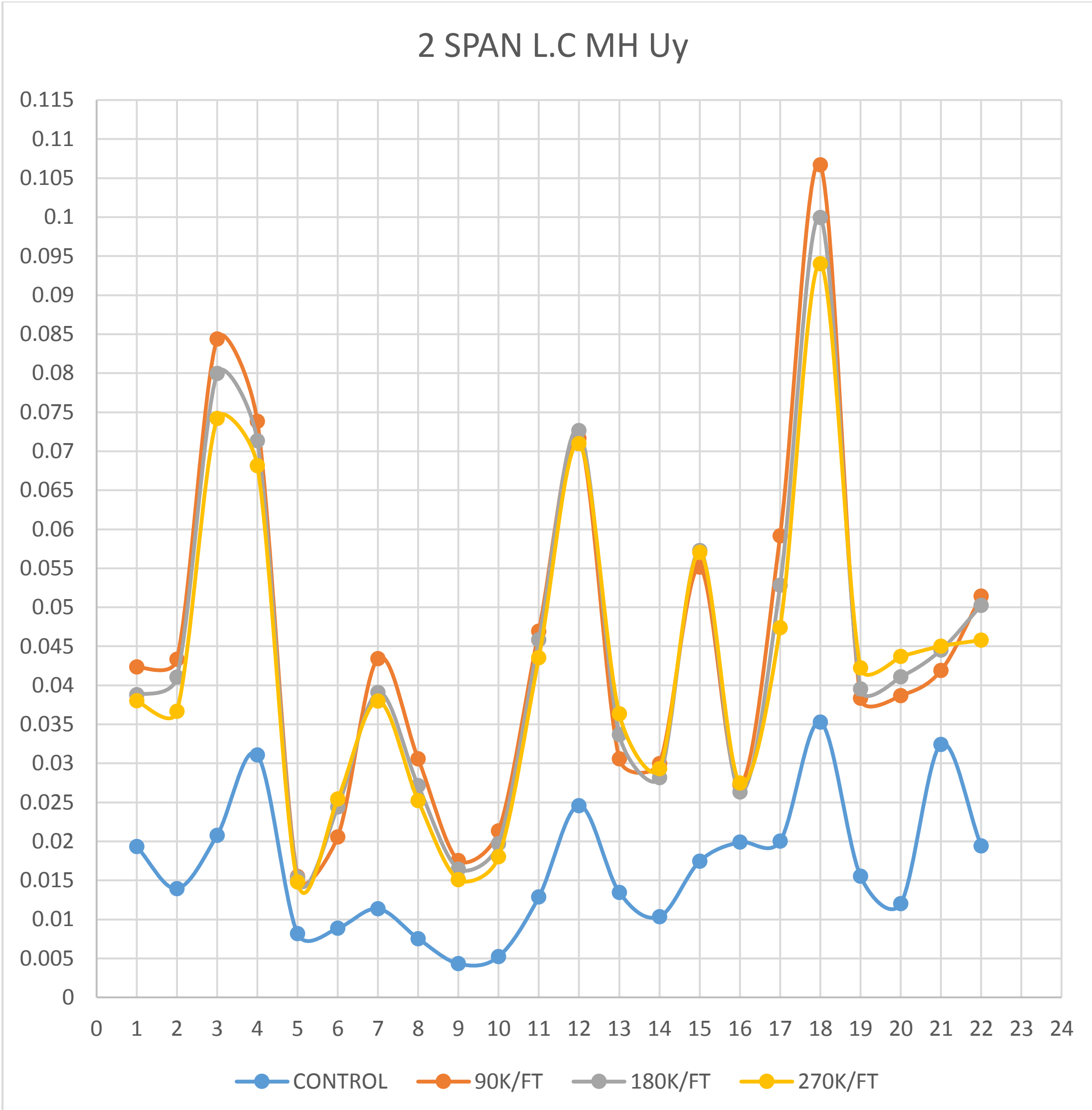


Fig. 4-20 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the two span bridge.

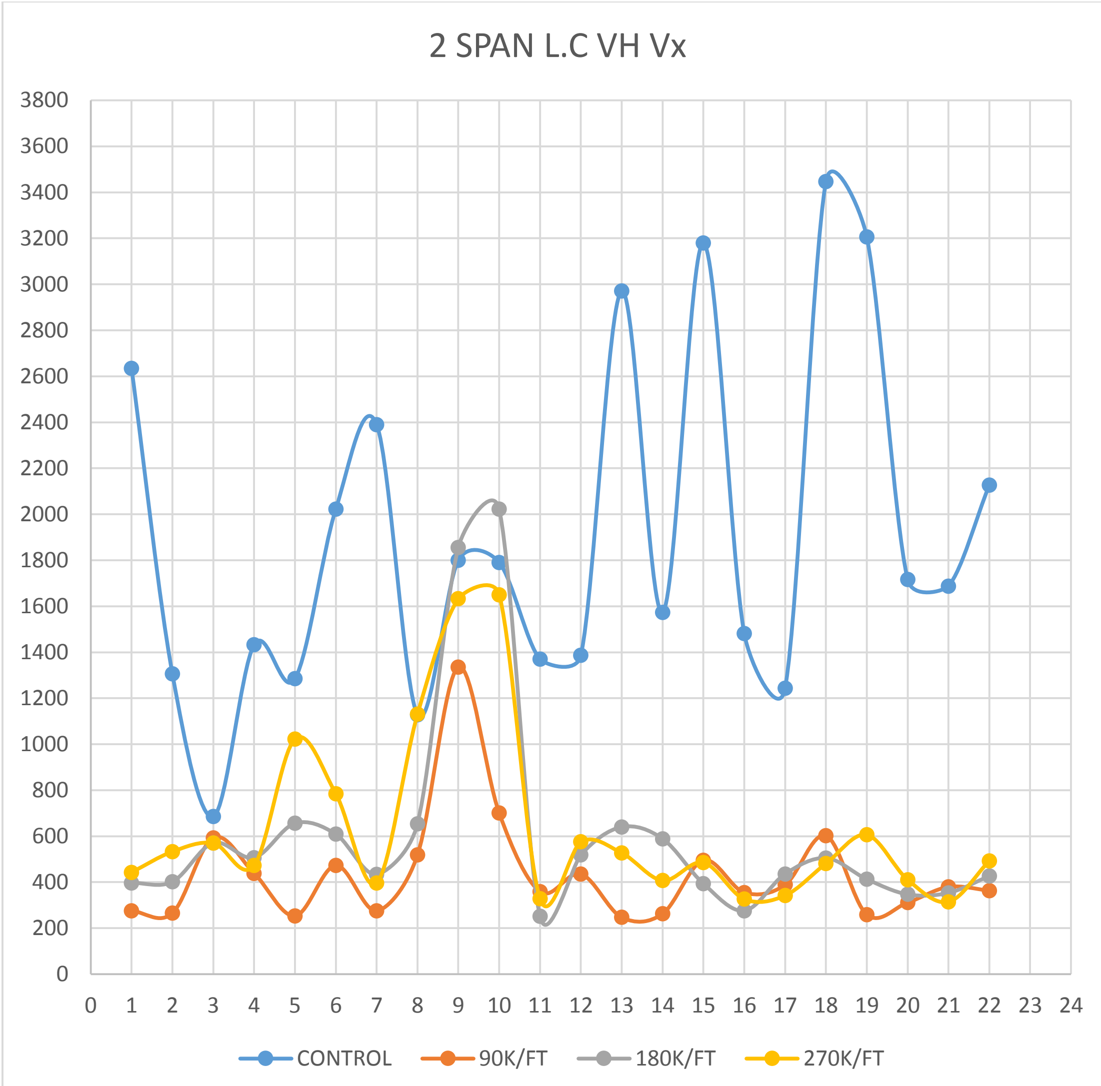


Fig. 4-21 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

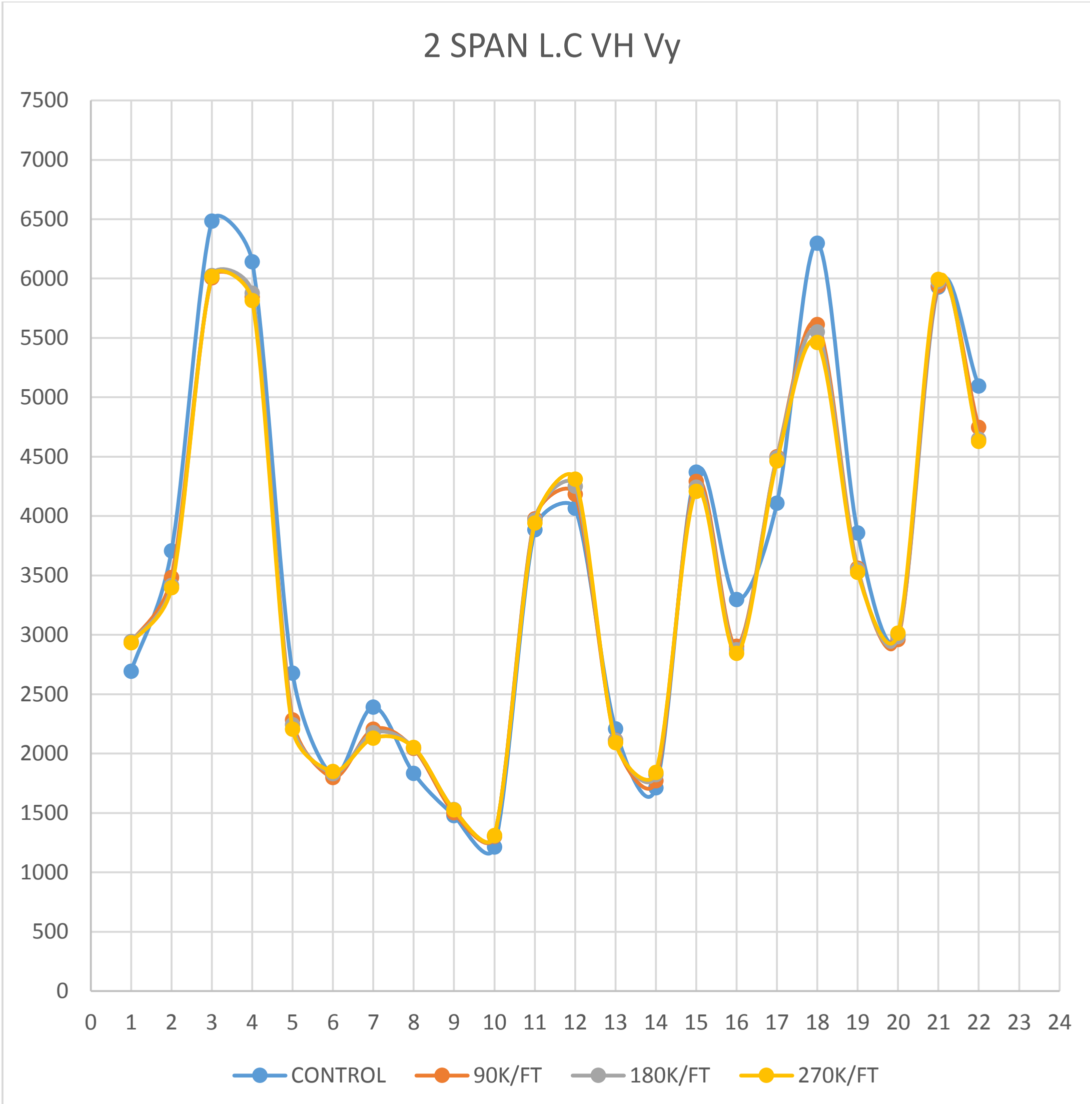


Fig. 4-22 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

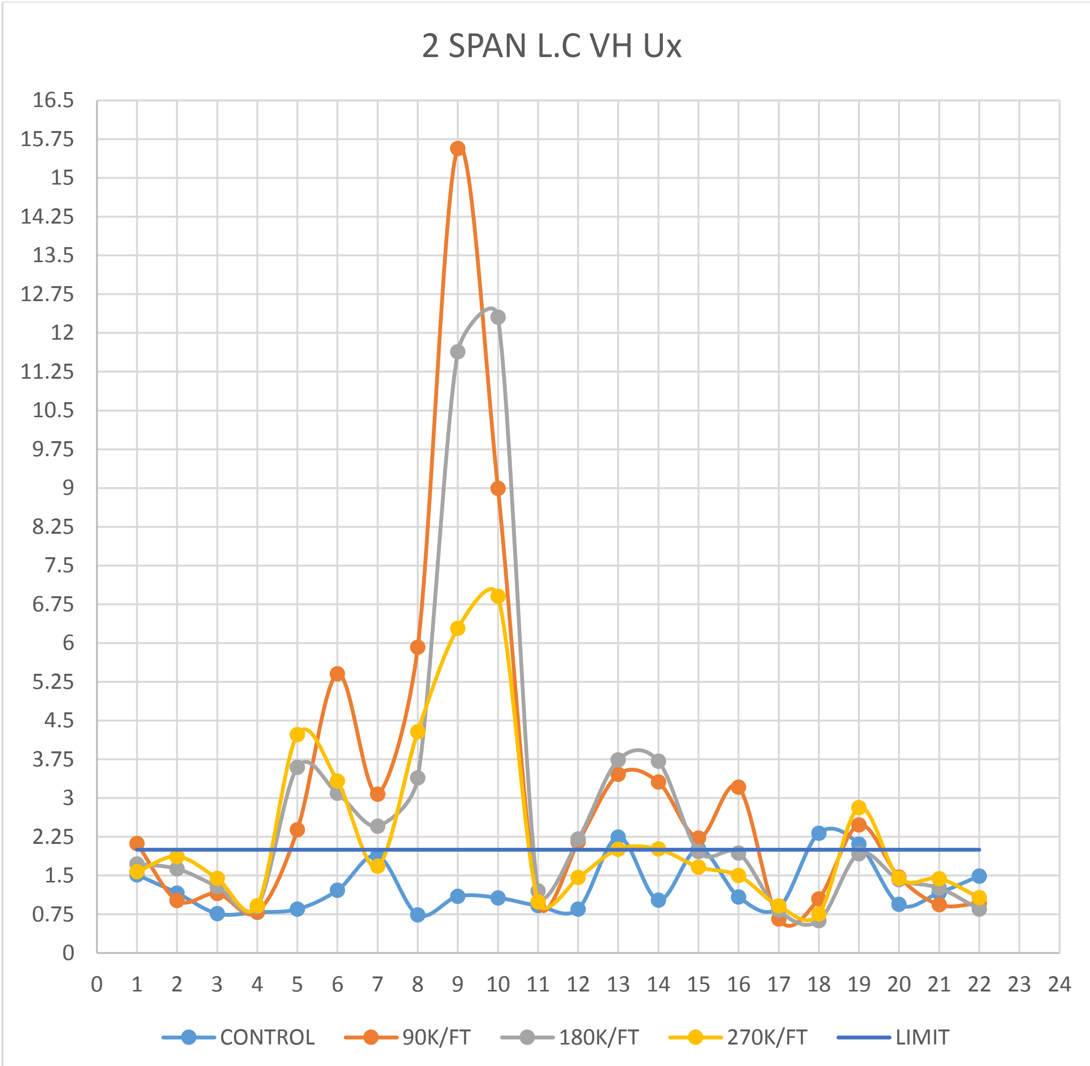


Fig. 4-23 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

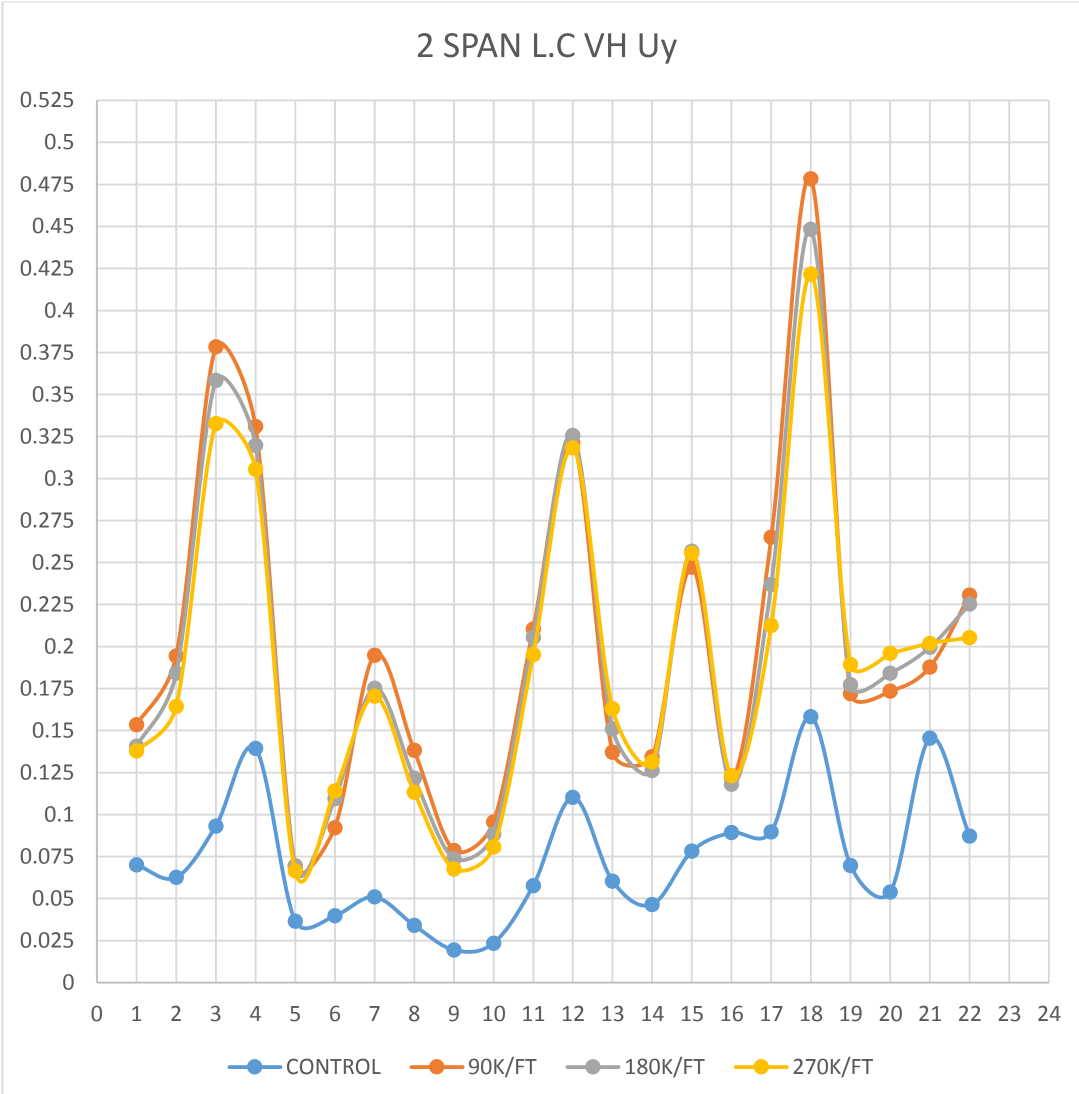


Fig. 4-24 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the two span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 2 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 2 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 2 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 3447.038

90 K/Ft = 1335.274

180 K/Ft = 2021.834

270 K/Ft = 1650.335

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

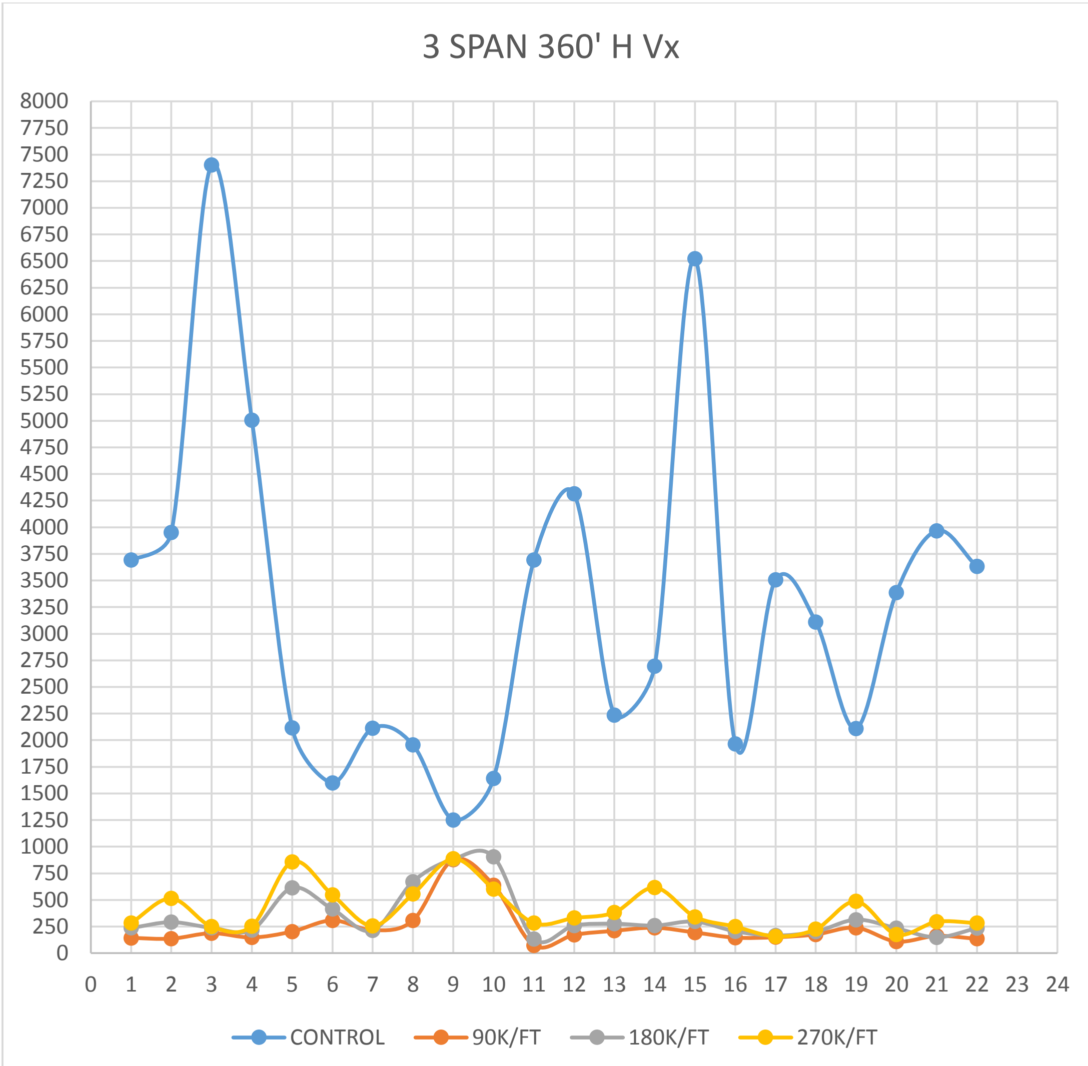


Fig. 4-25 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

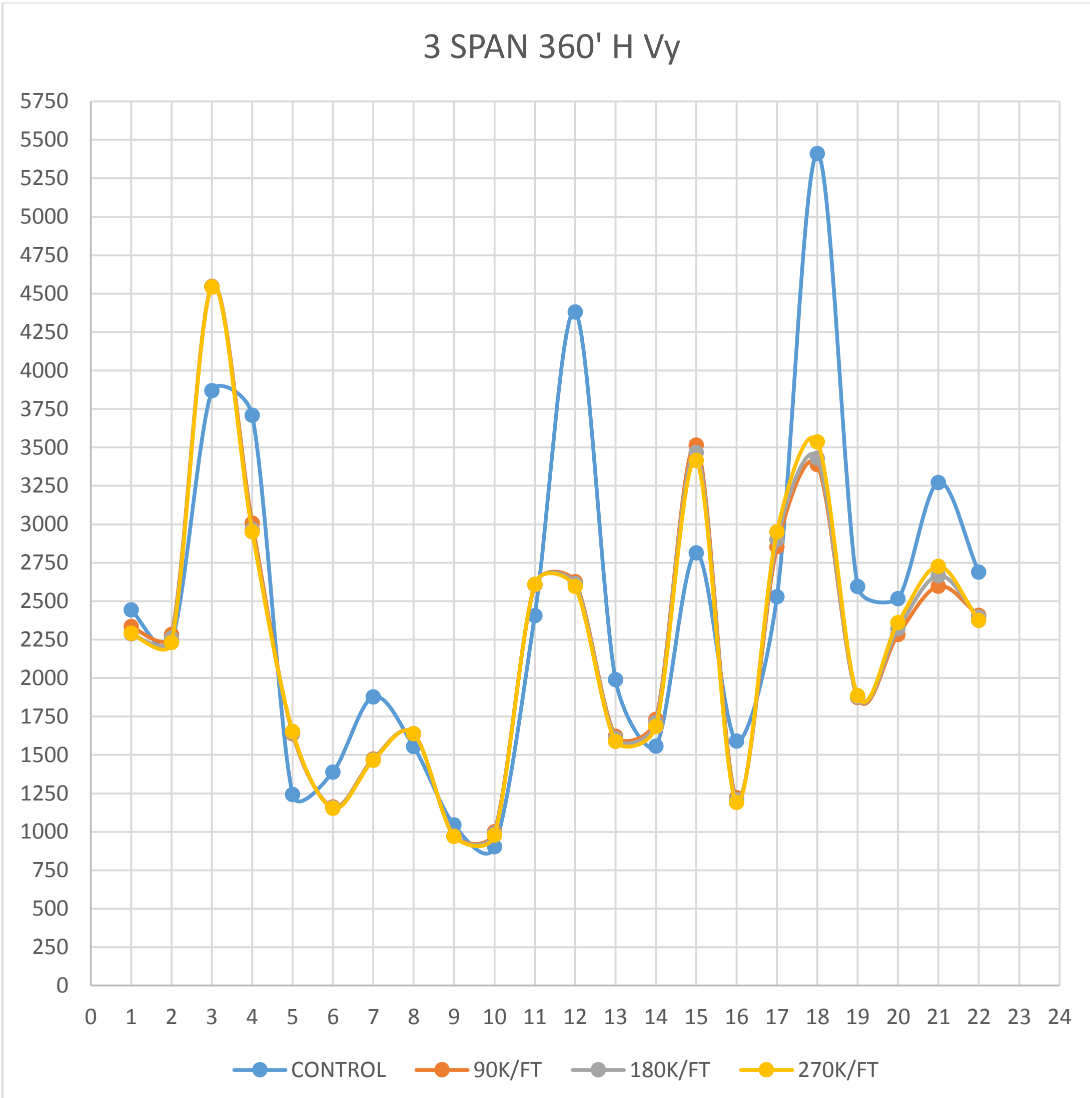


Fig. 4-26 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

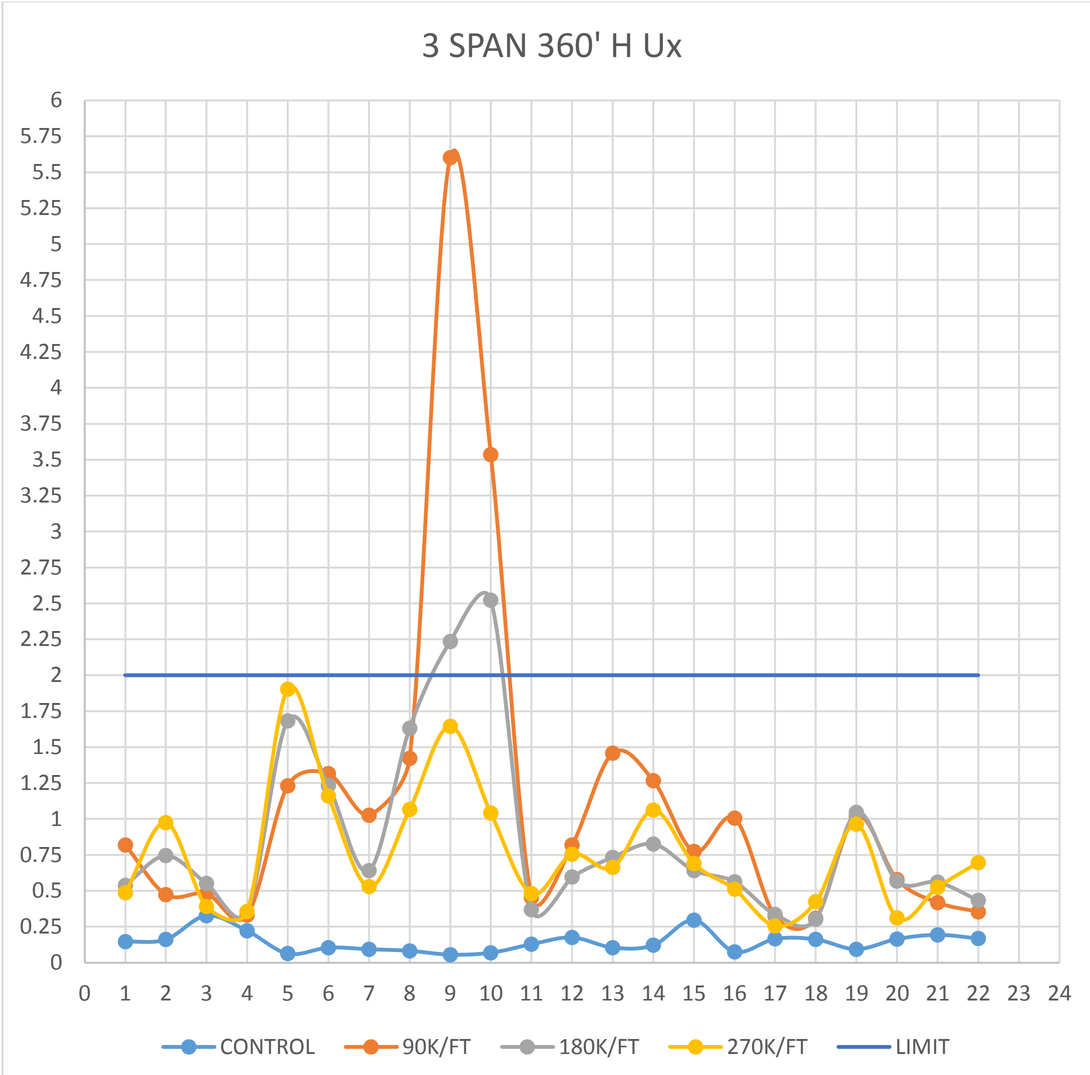


Fig. 4-27 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

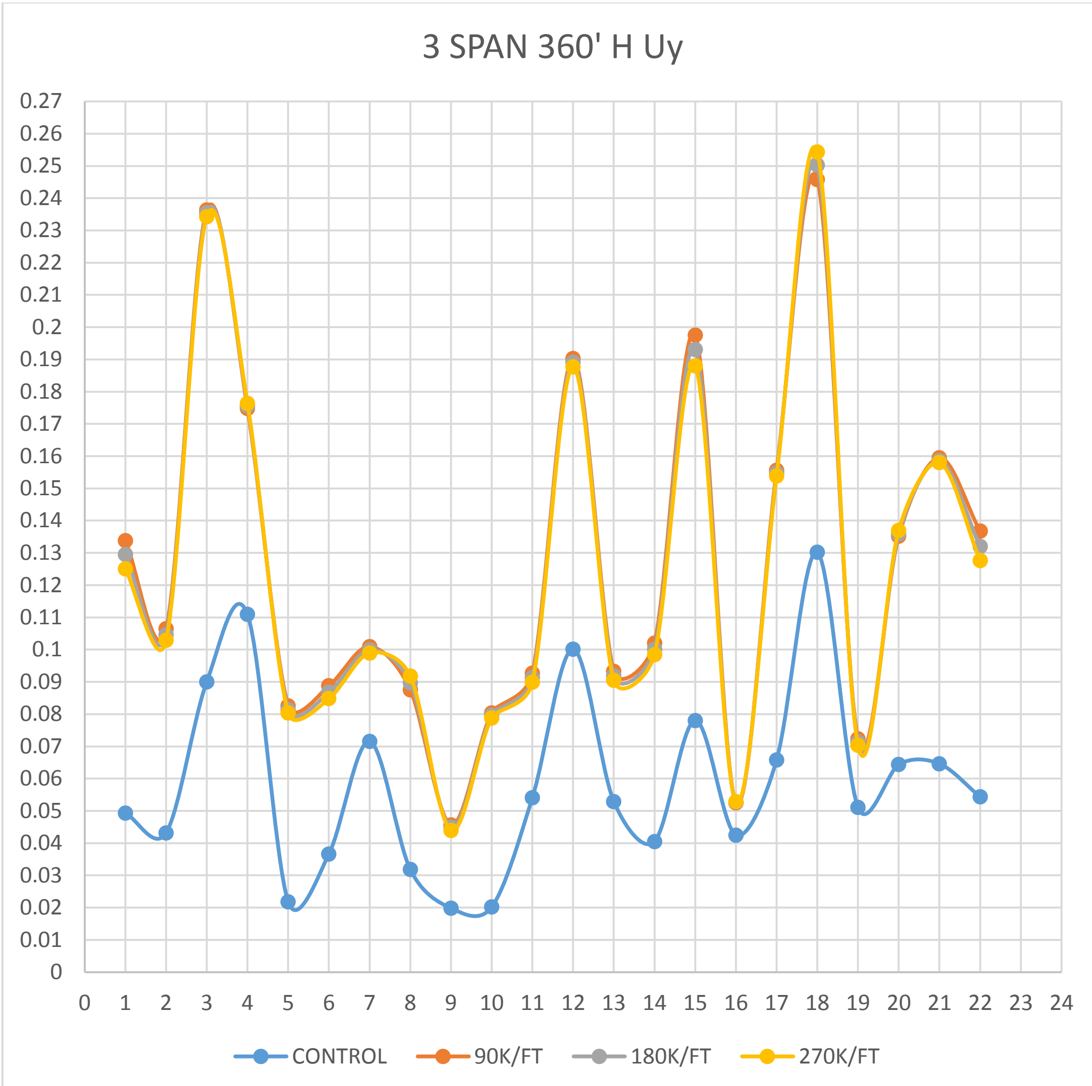


Fig. 4-28 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

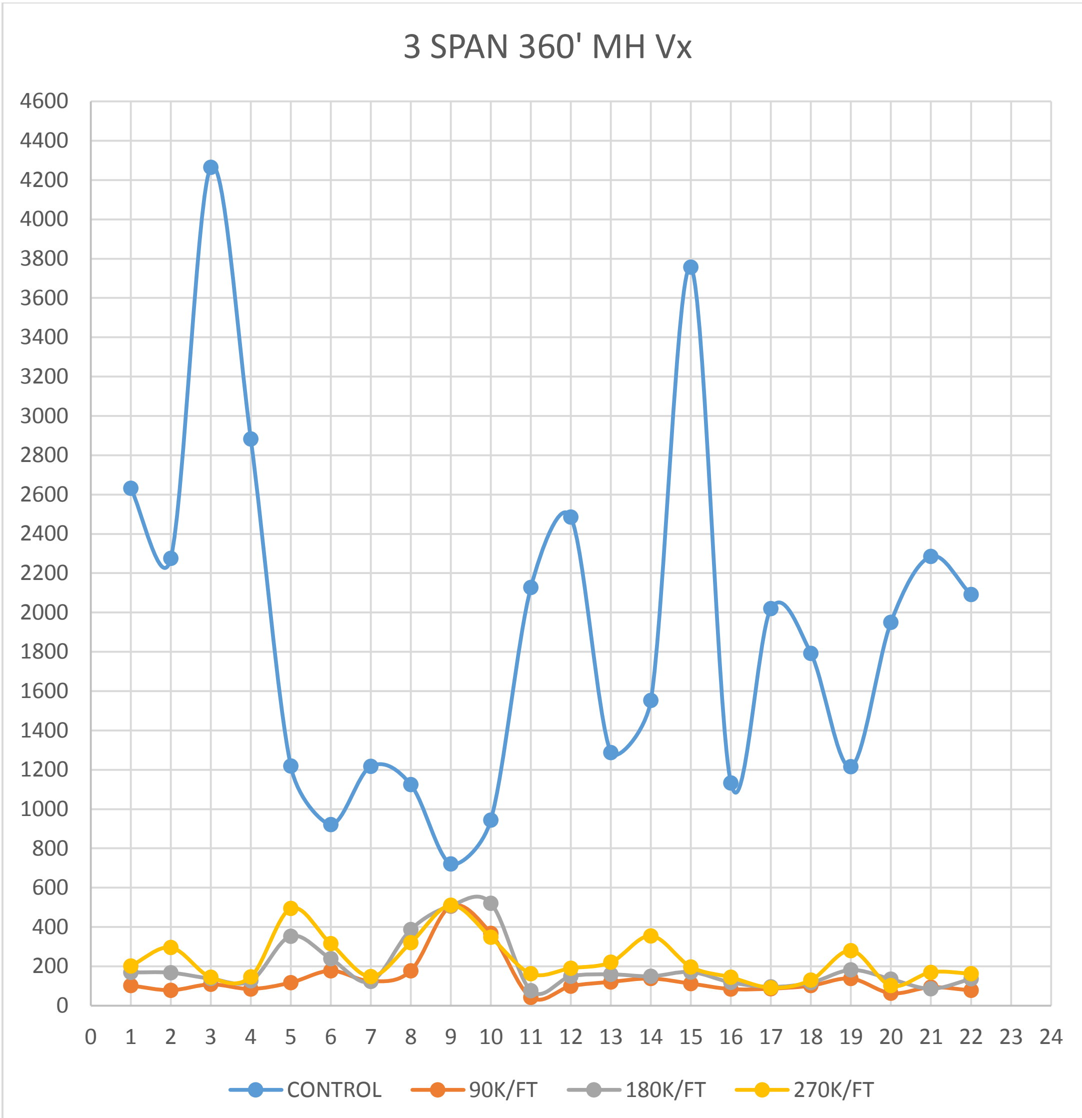


Fig. 4-29 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

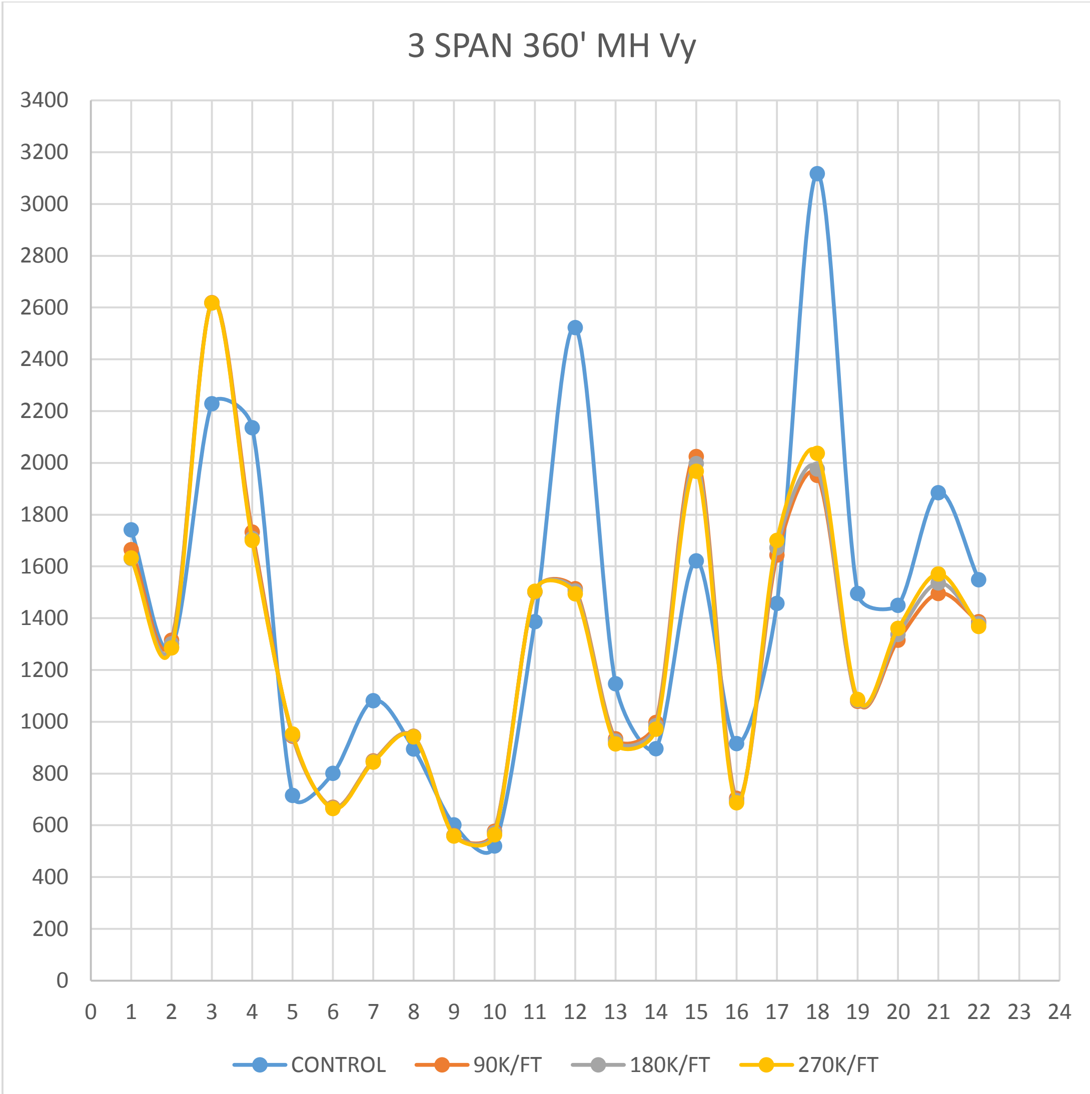


Fig. 4-30 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

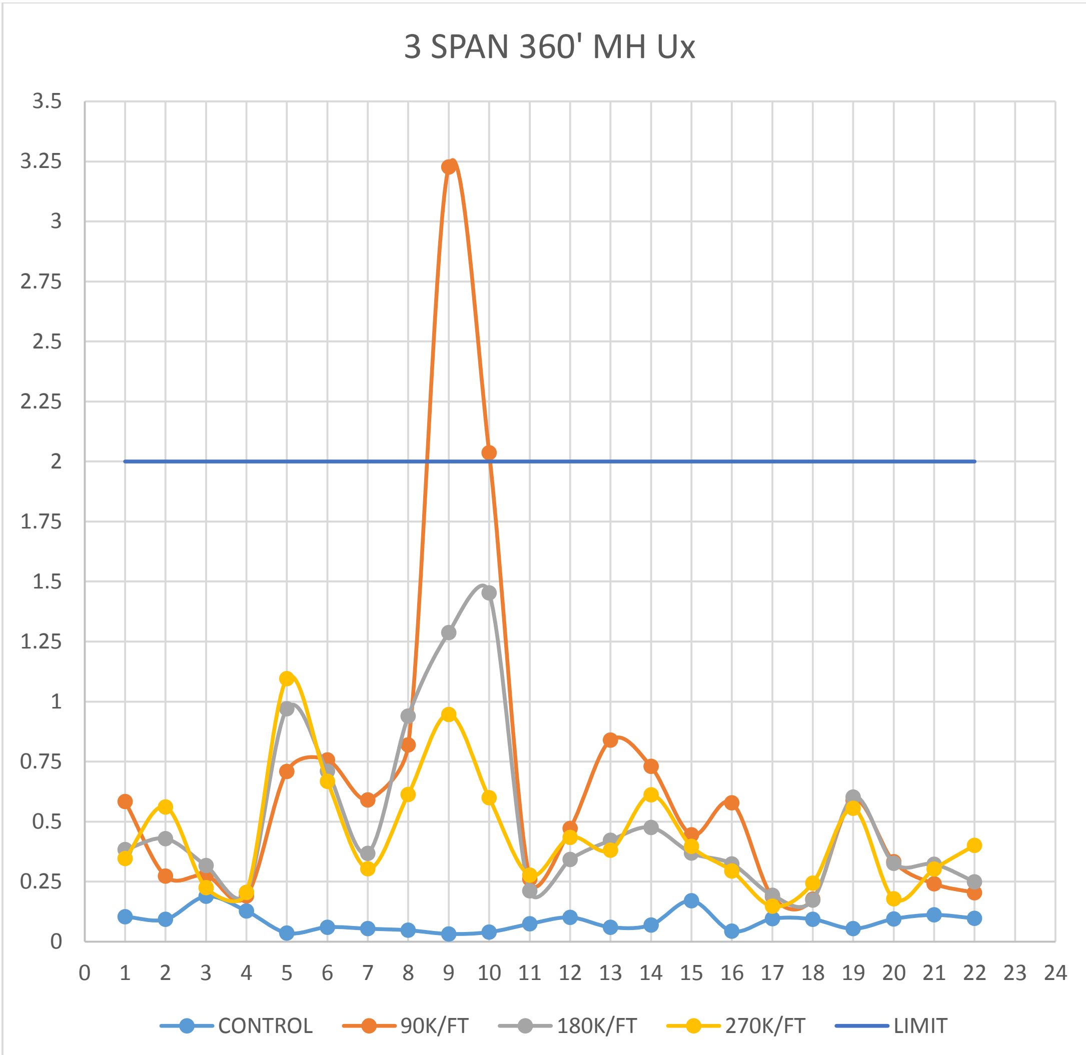


Fig. 4-31 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

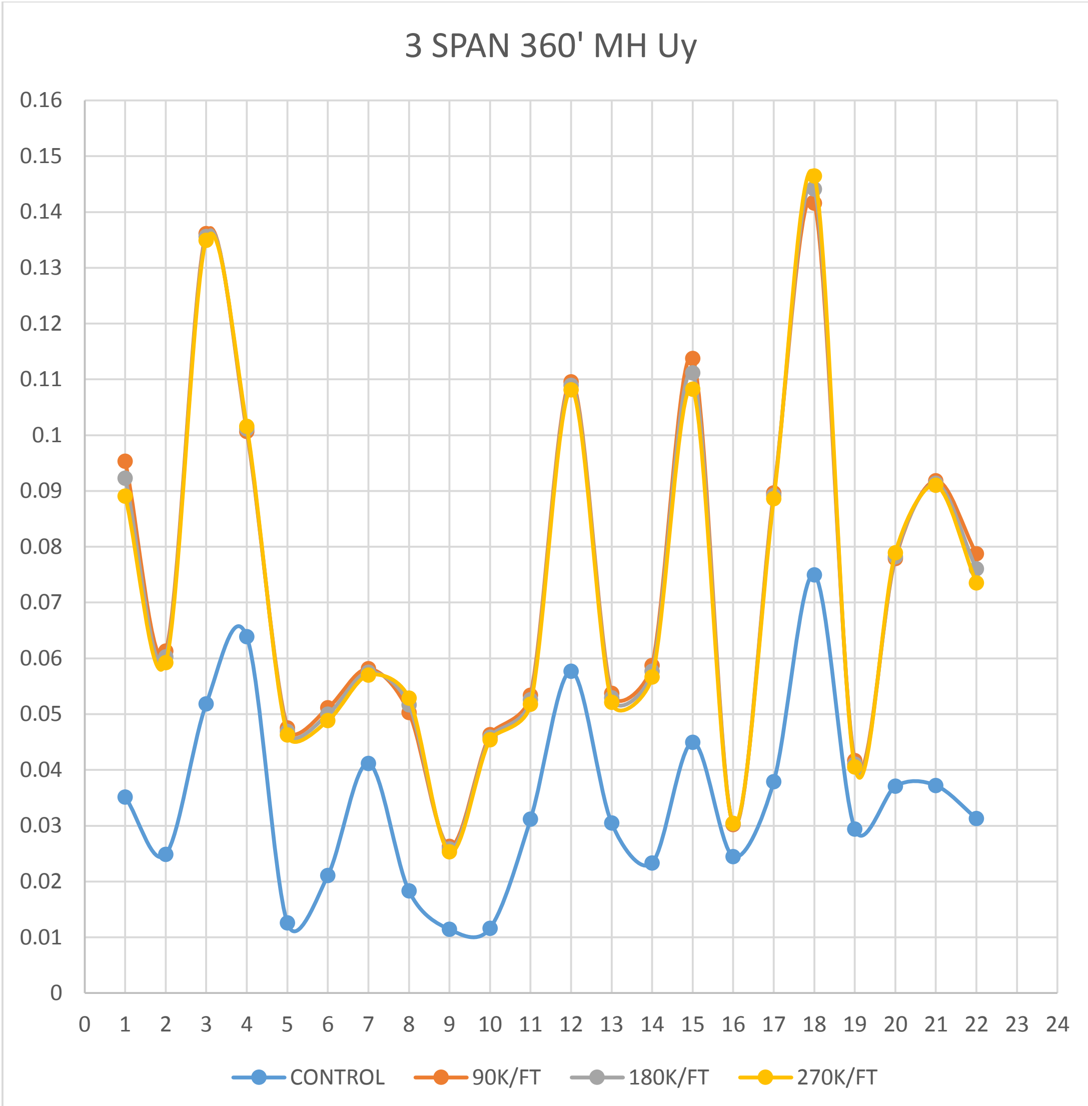


Fig. 4-32 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

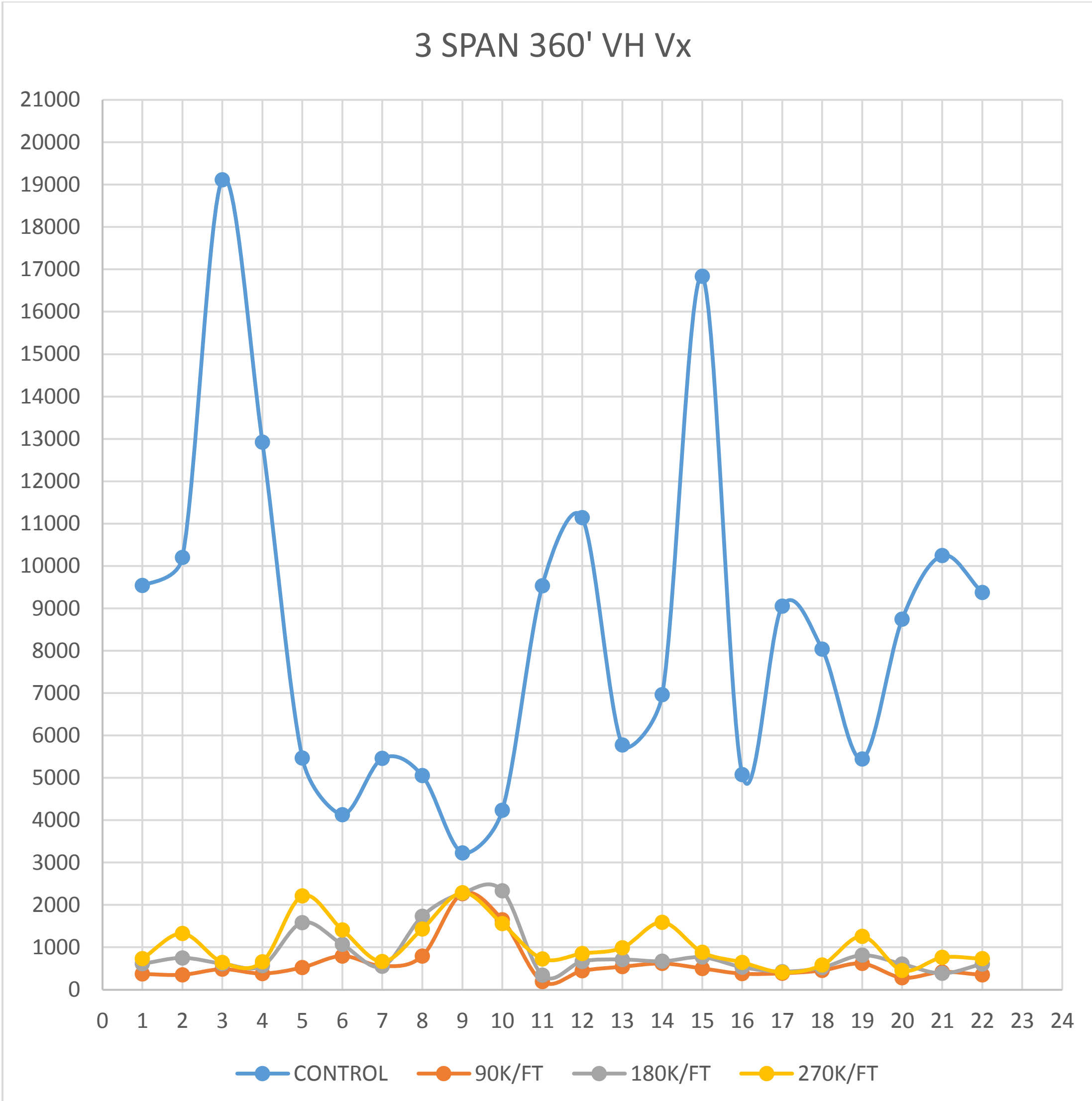


Fig. 4-33 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

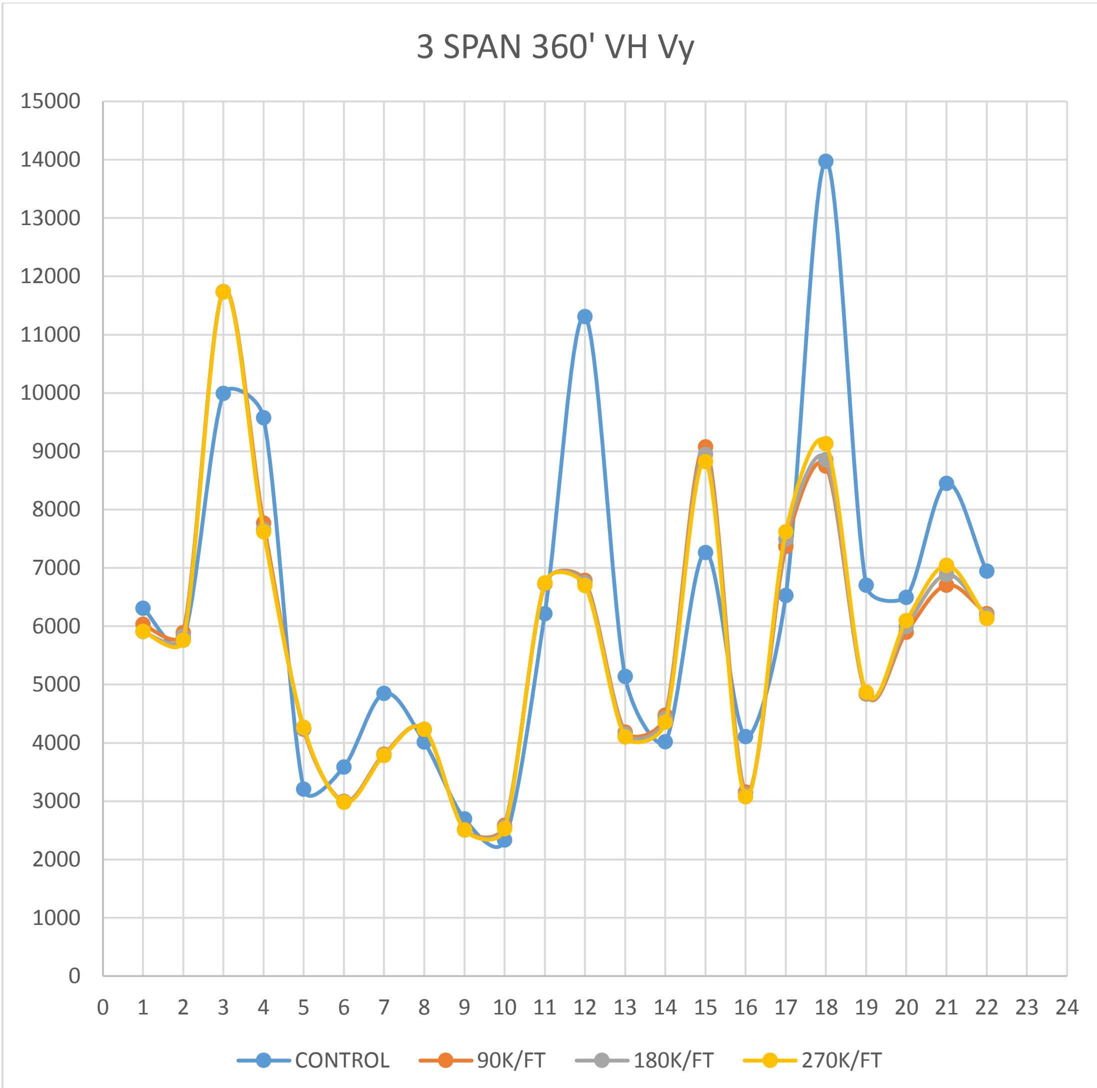


Fig. 4-34 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

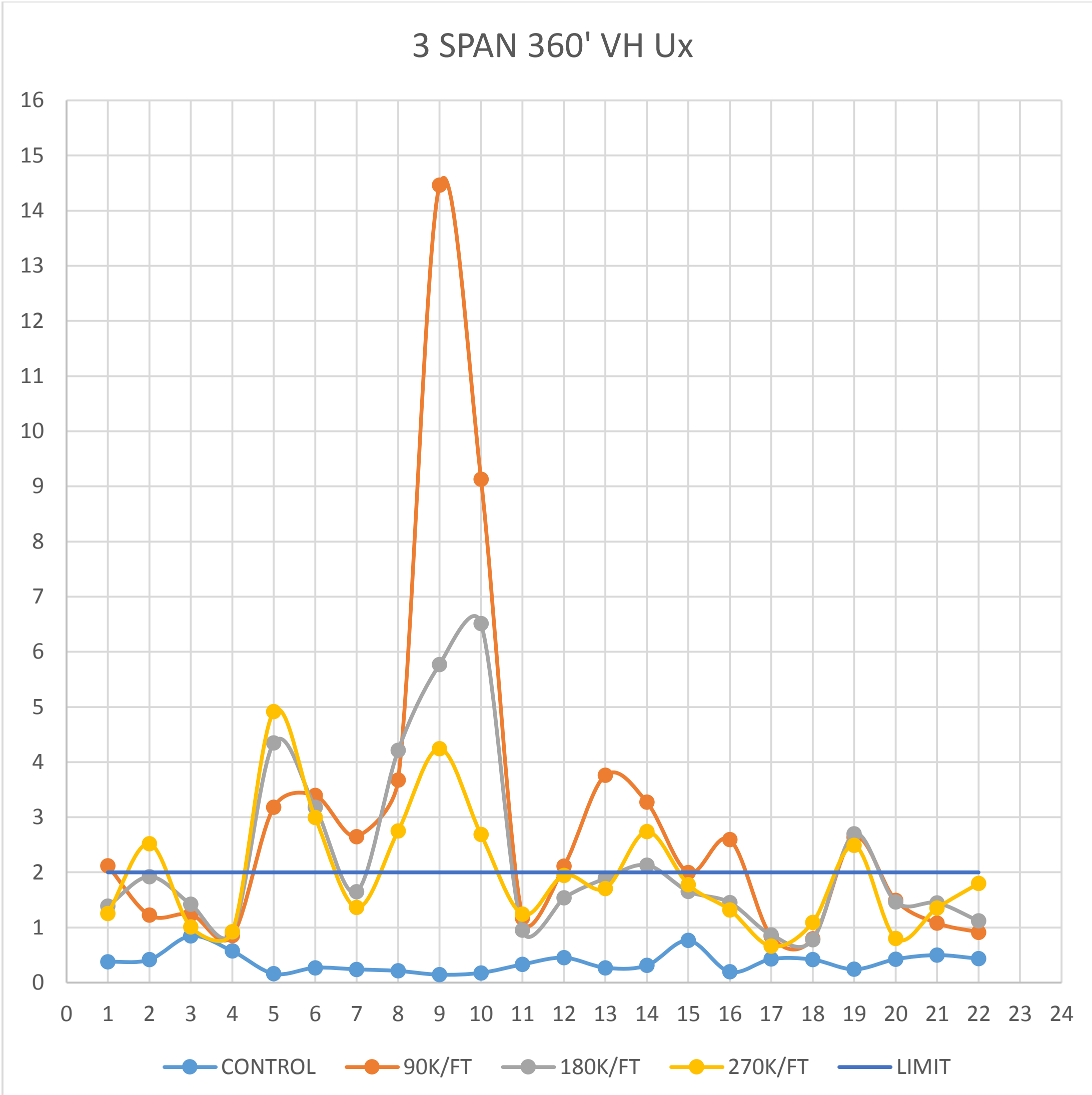


Fig. 4-35 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

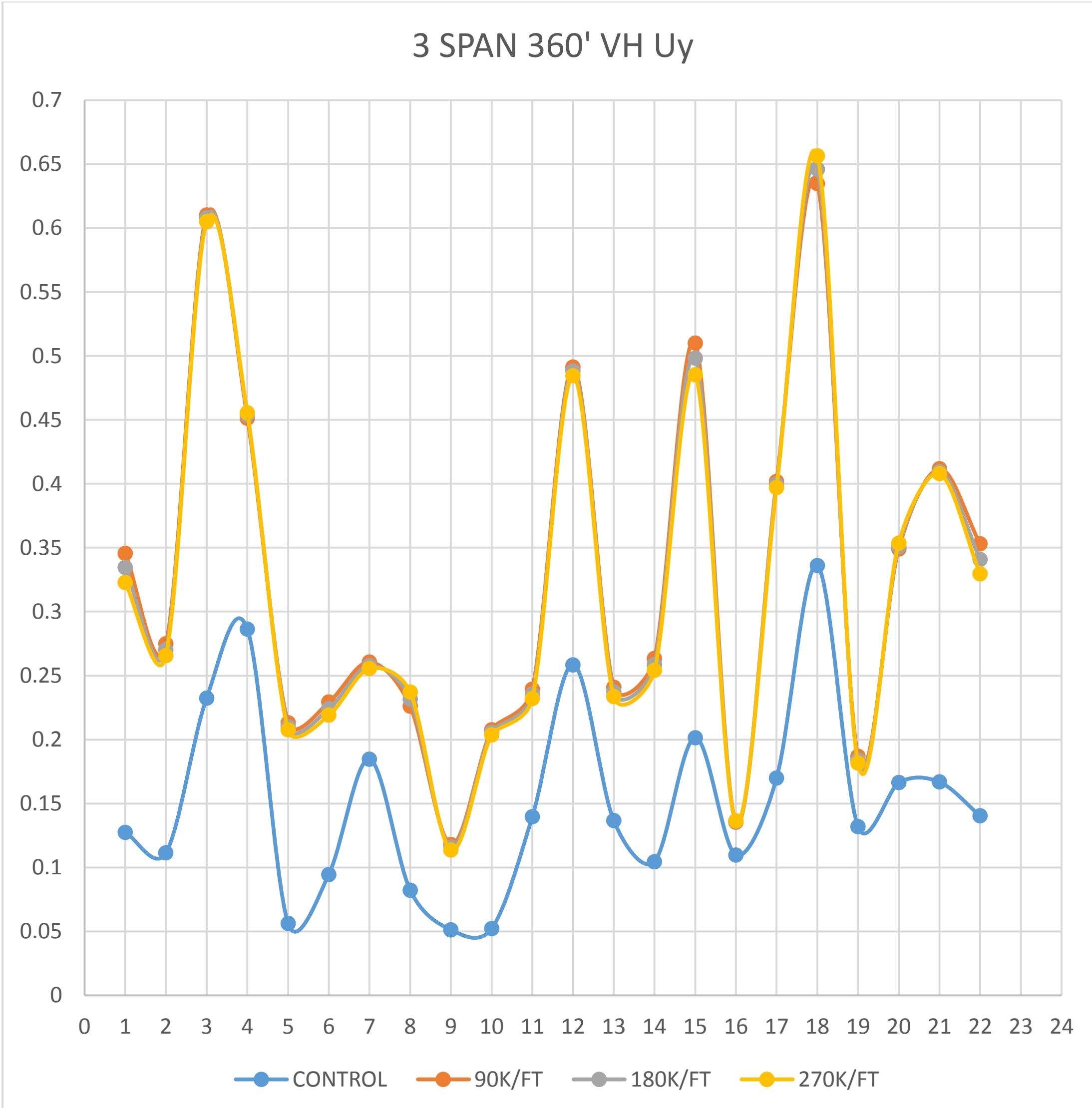


Fig. 4-36 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 19117.46

90 K/Ft = 2266.644

180 K/Ft = 2335.377

270 K/Ft = 2288.795

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

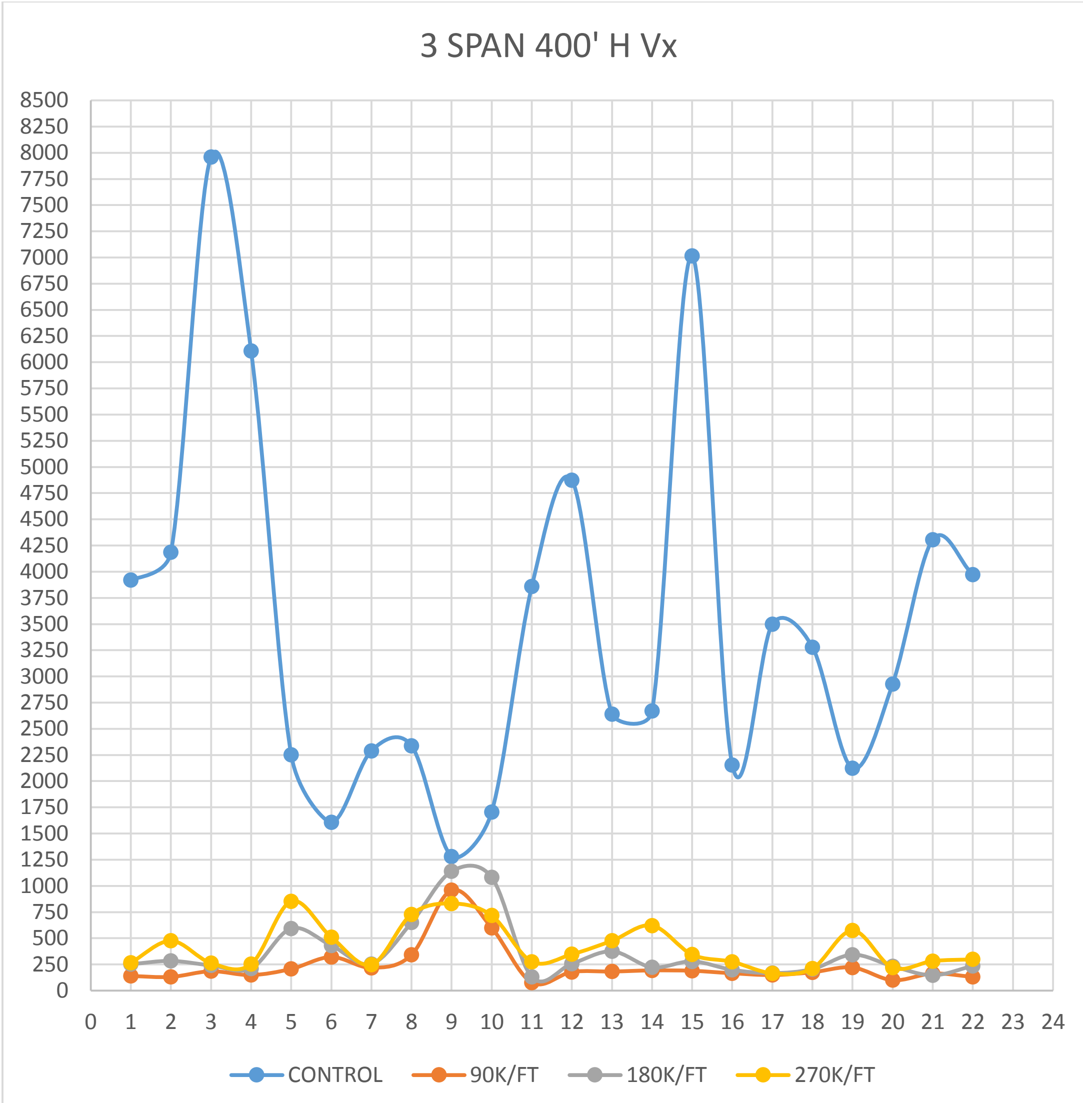


Fig. 4-37 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

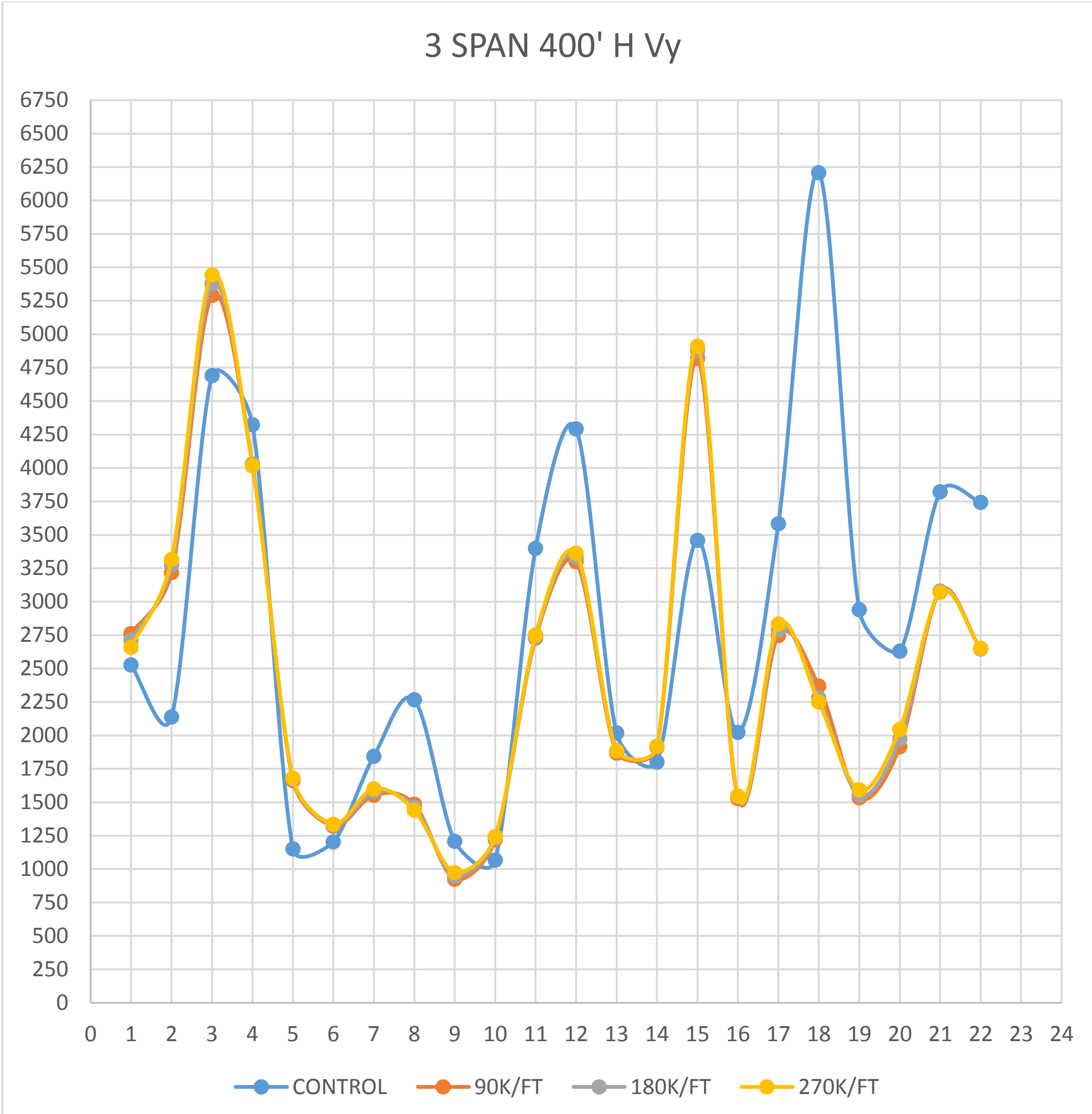


Fig. 4-38 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

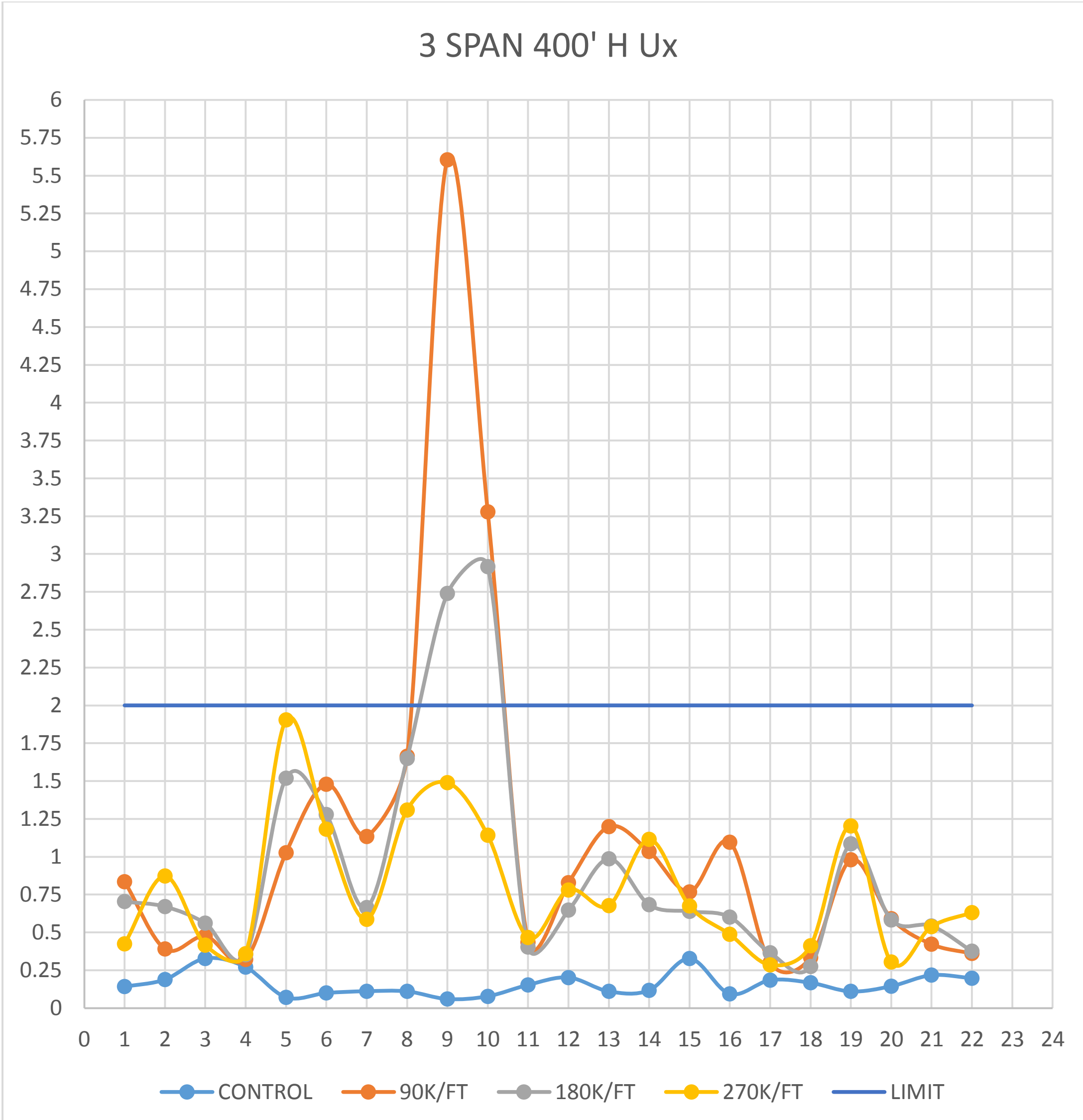


Fig. 4-39 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

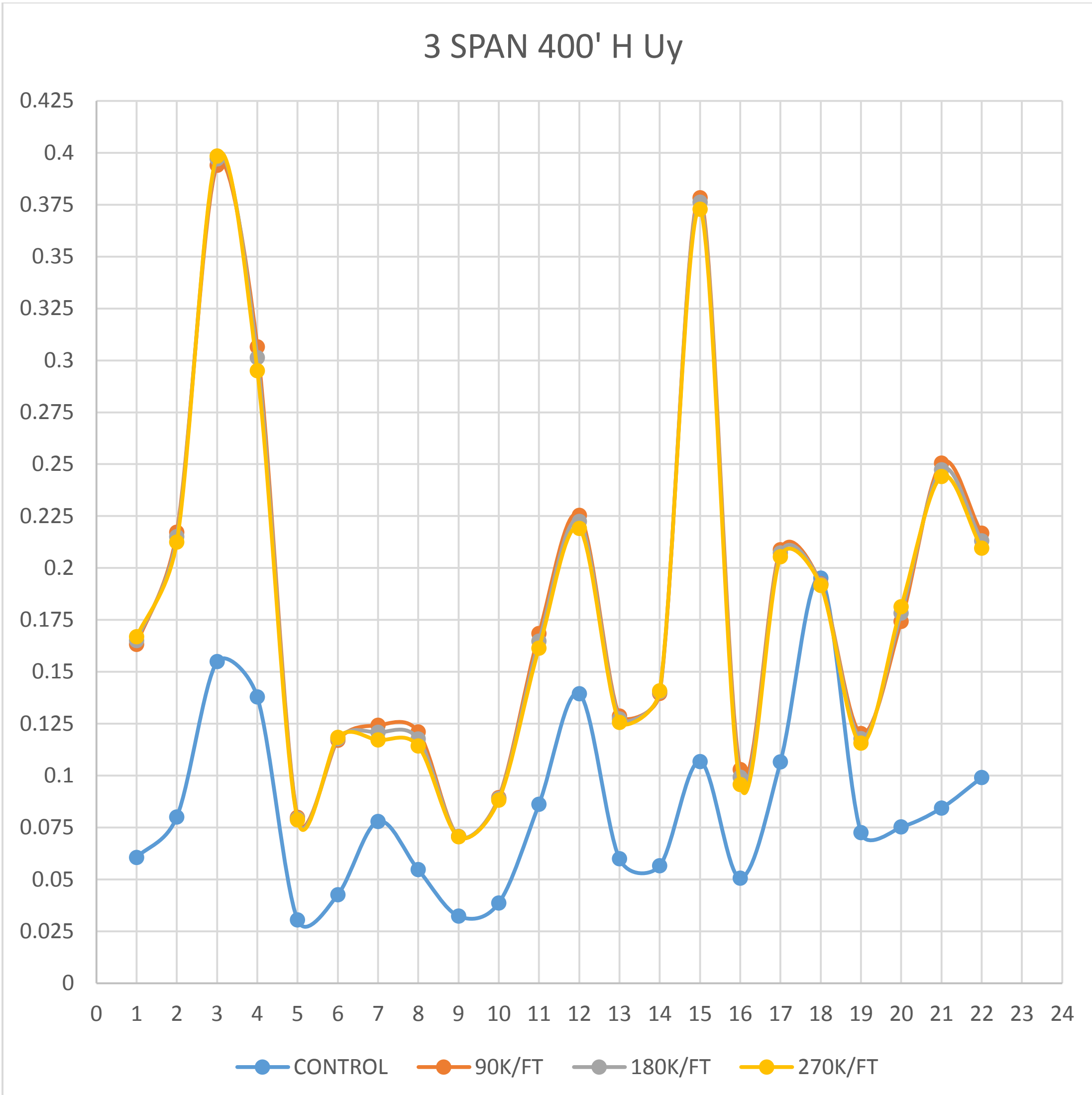


Fig. 4-40 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

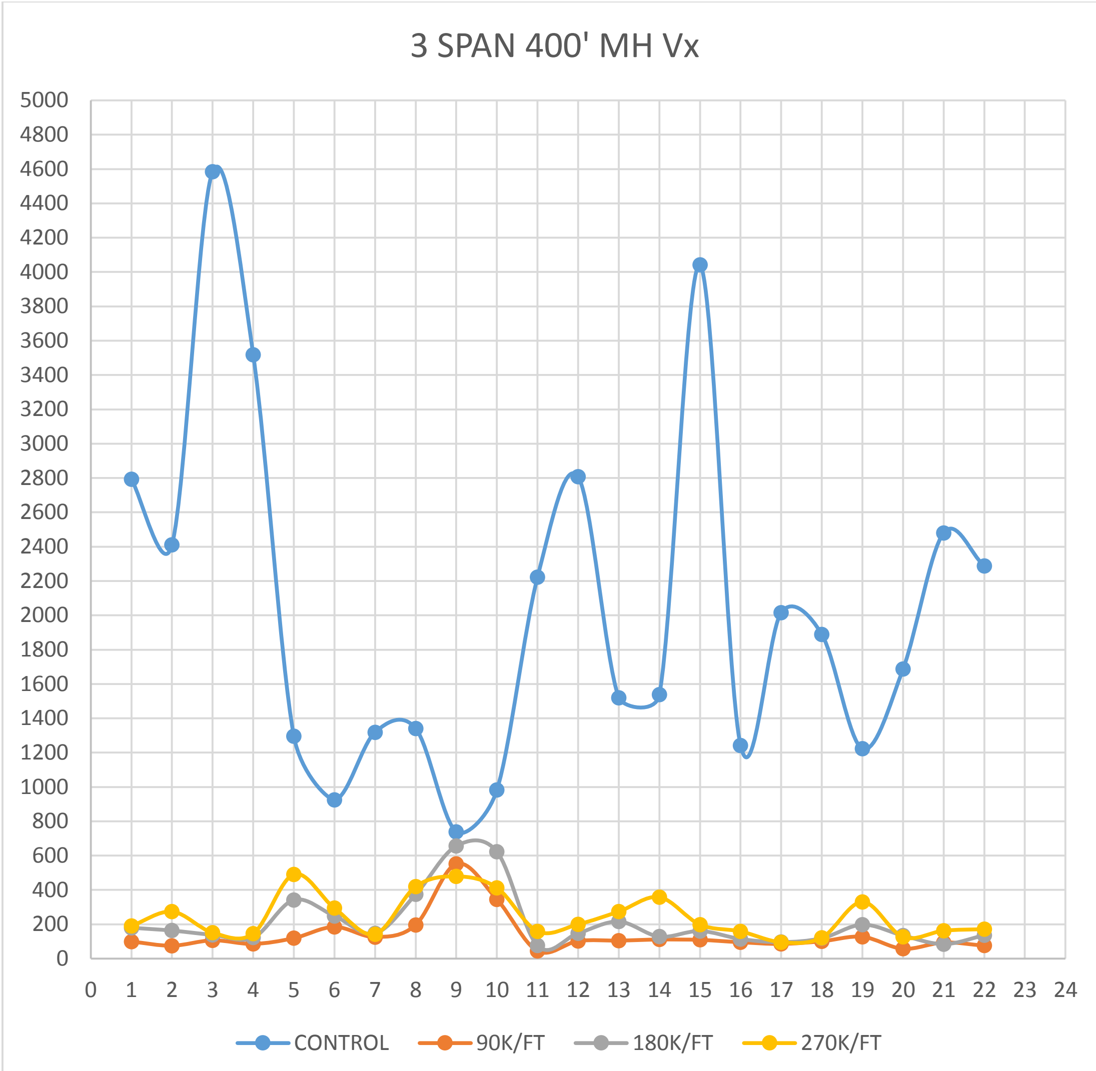


Fig. 4-41 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

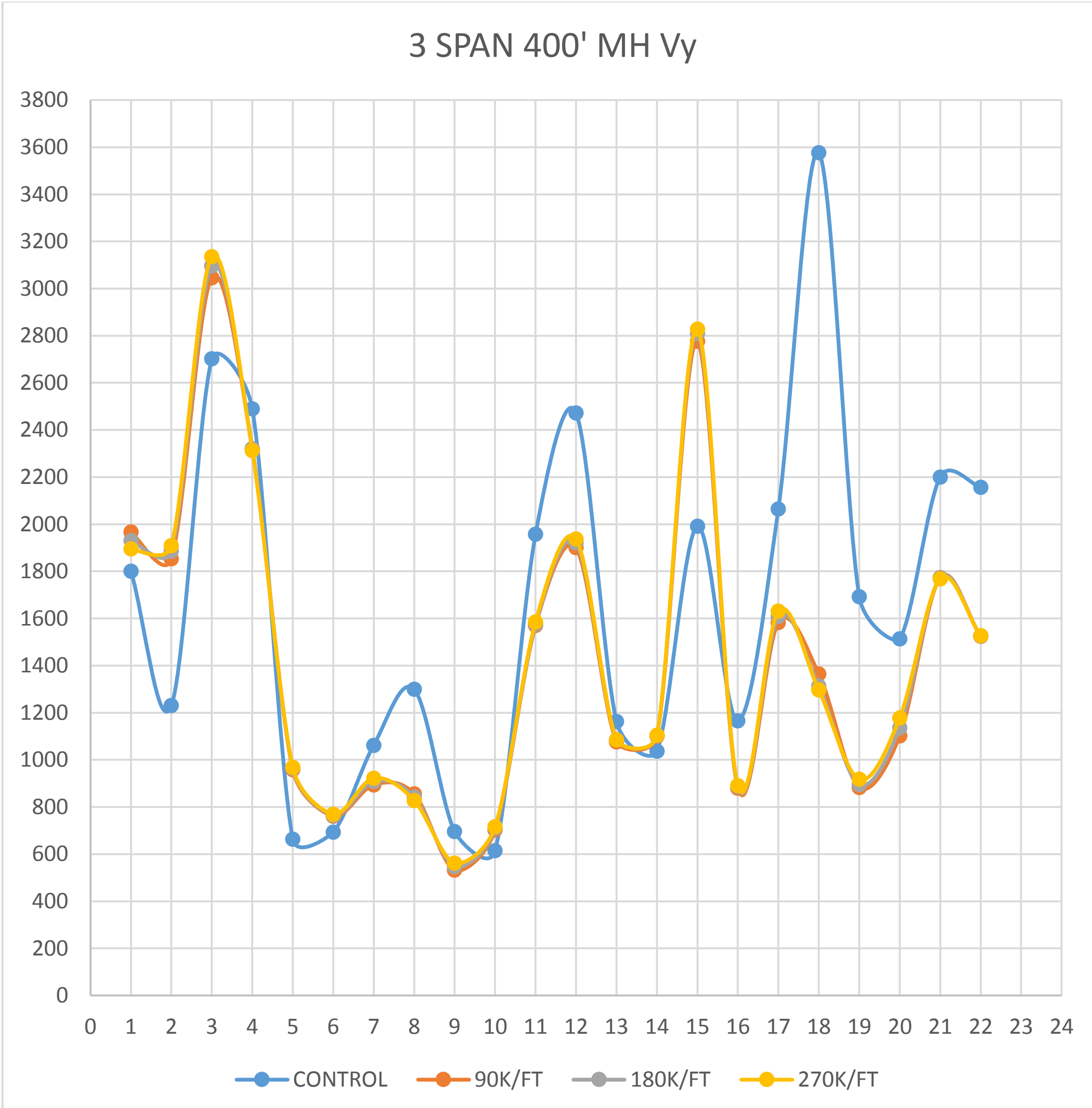


Fig. 4-42 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

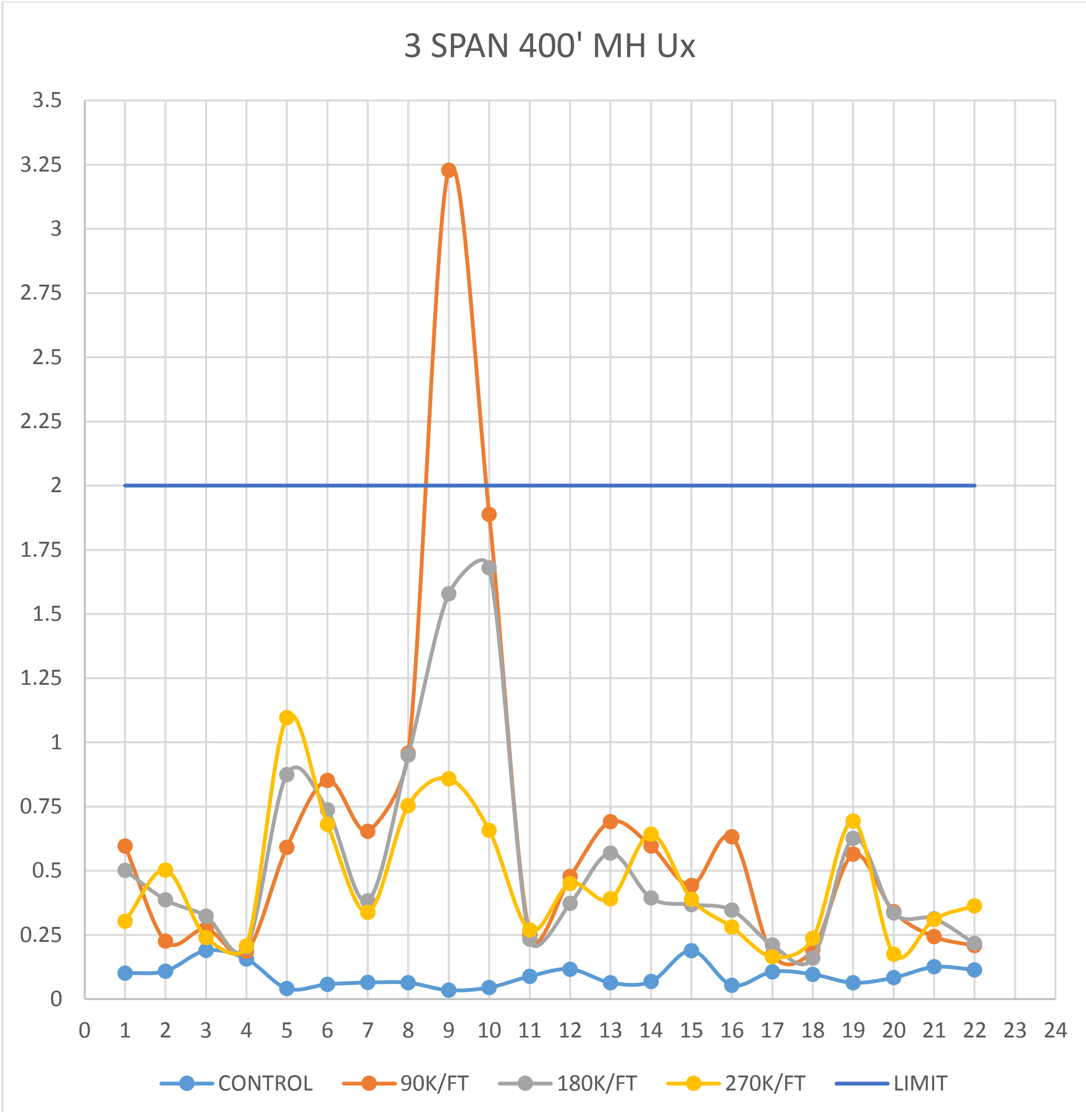


Fig. 4-43 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

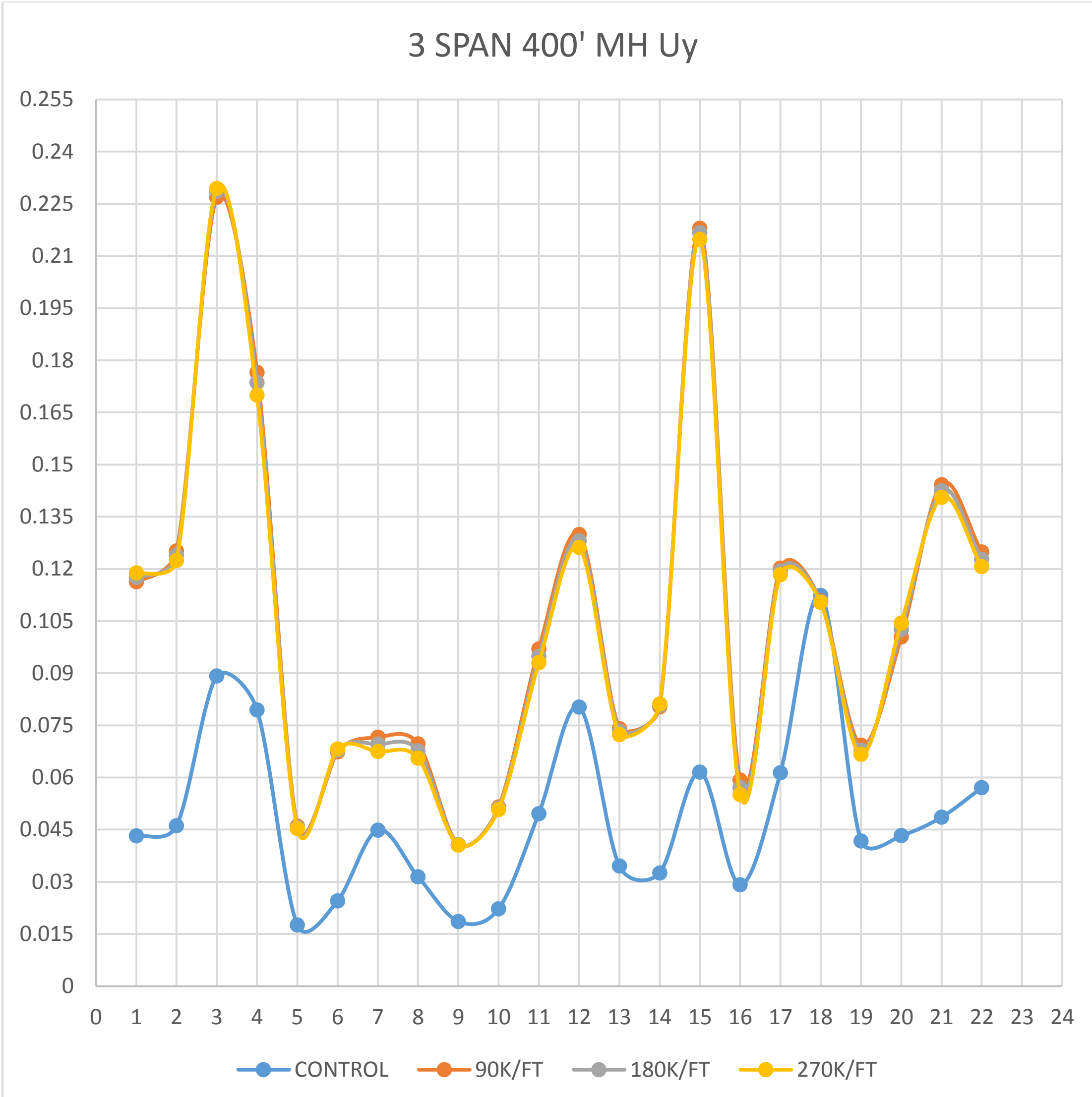


Fig. 4-44 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

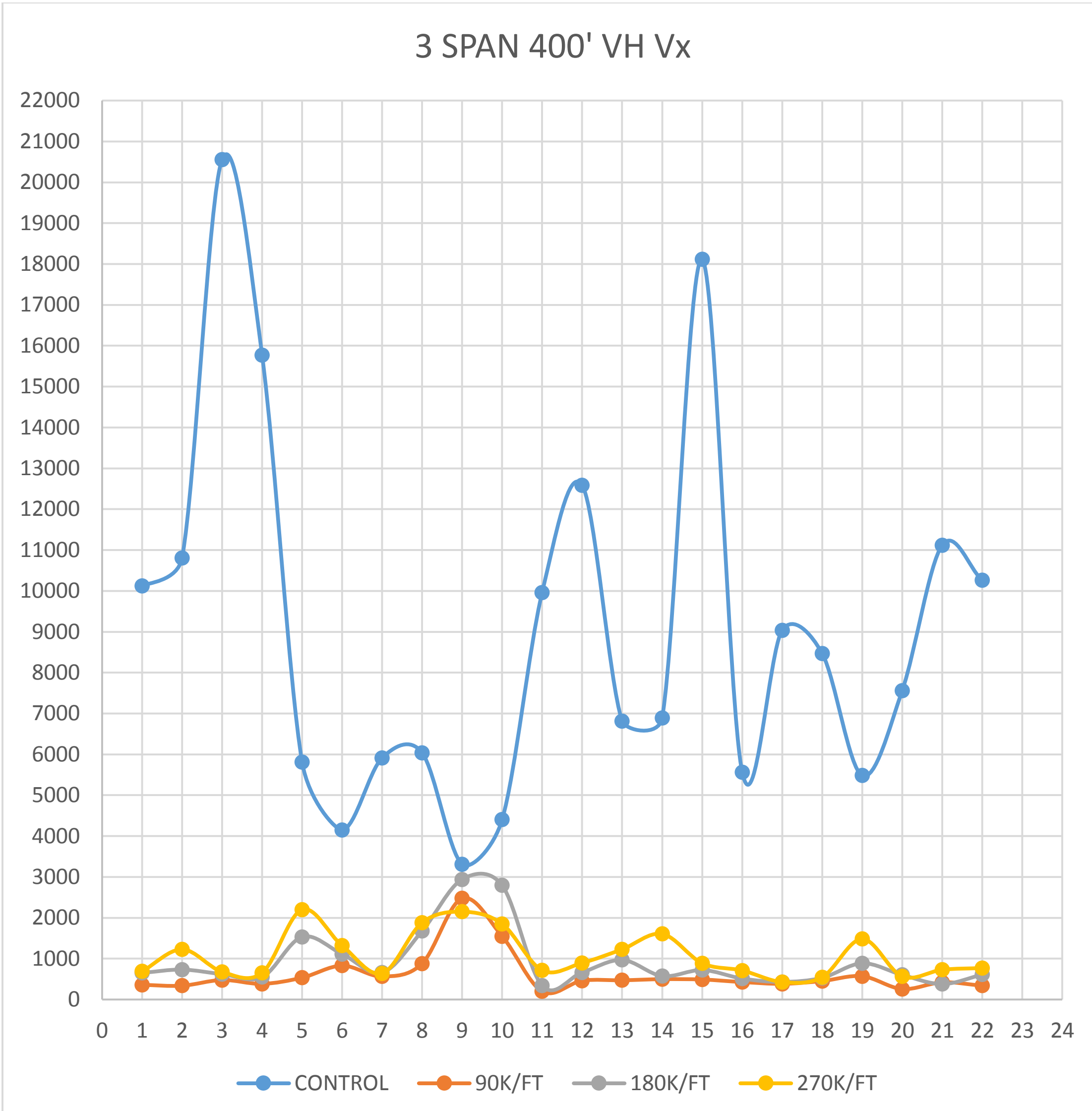


Fig. 4-45 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

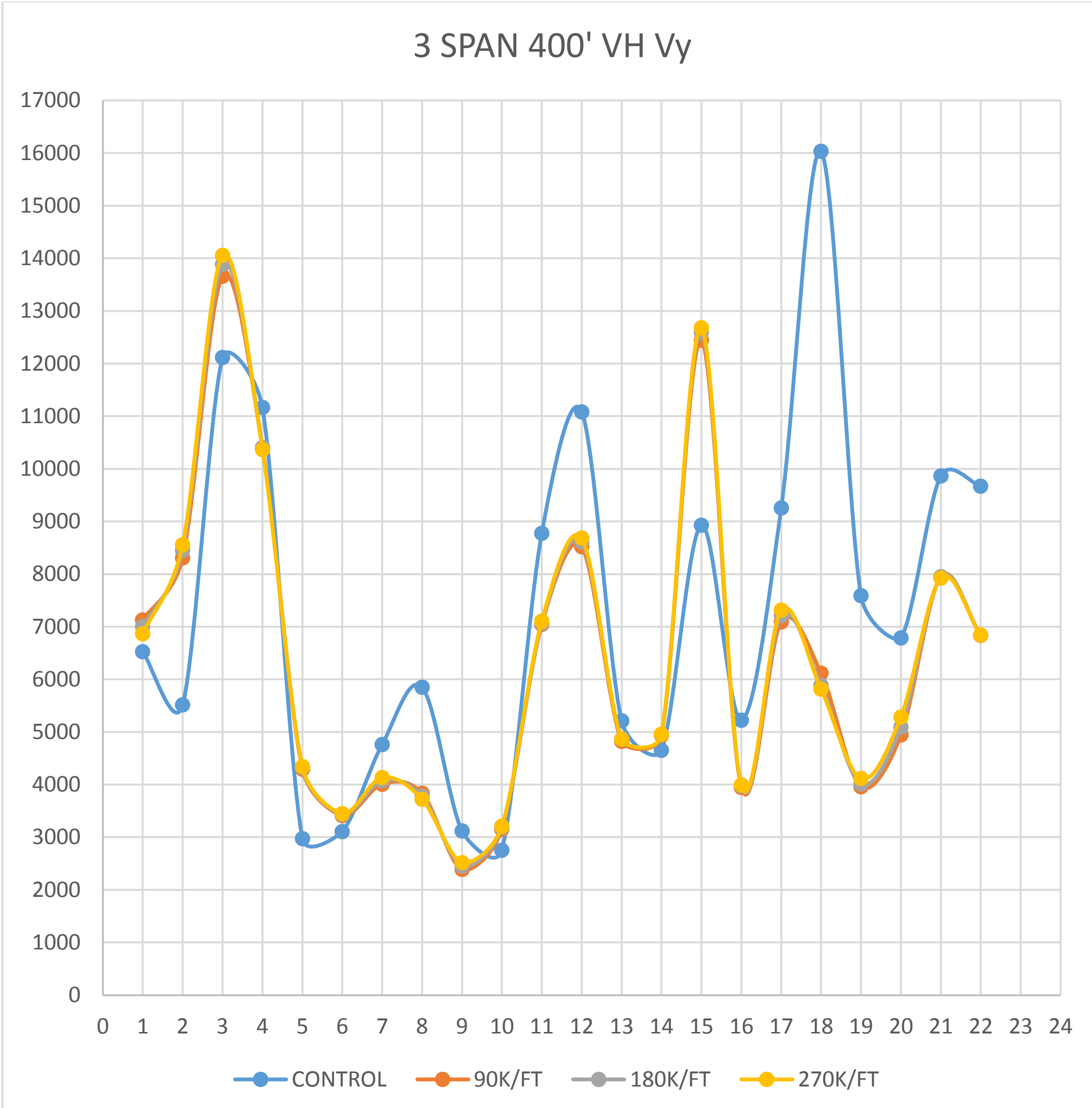


Fig. 4-46 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

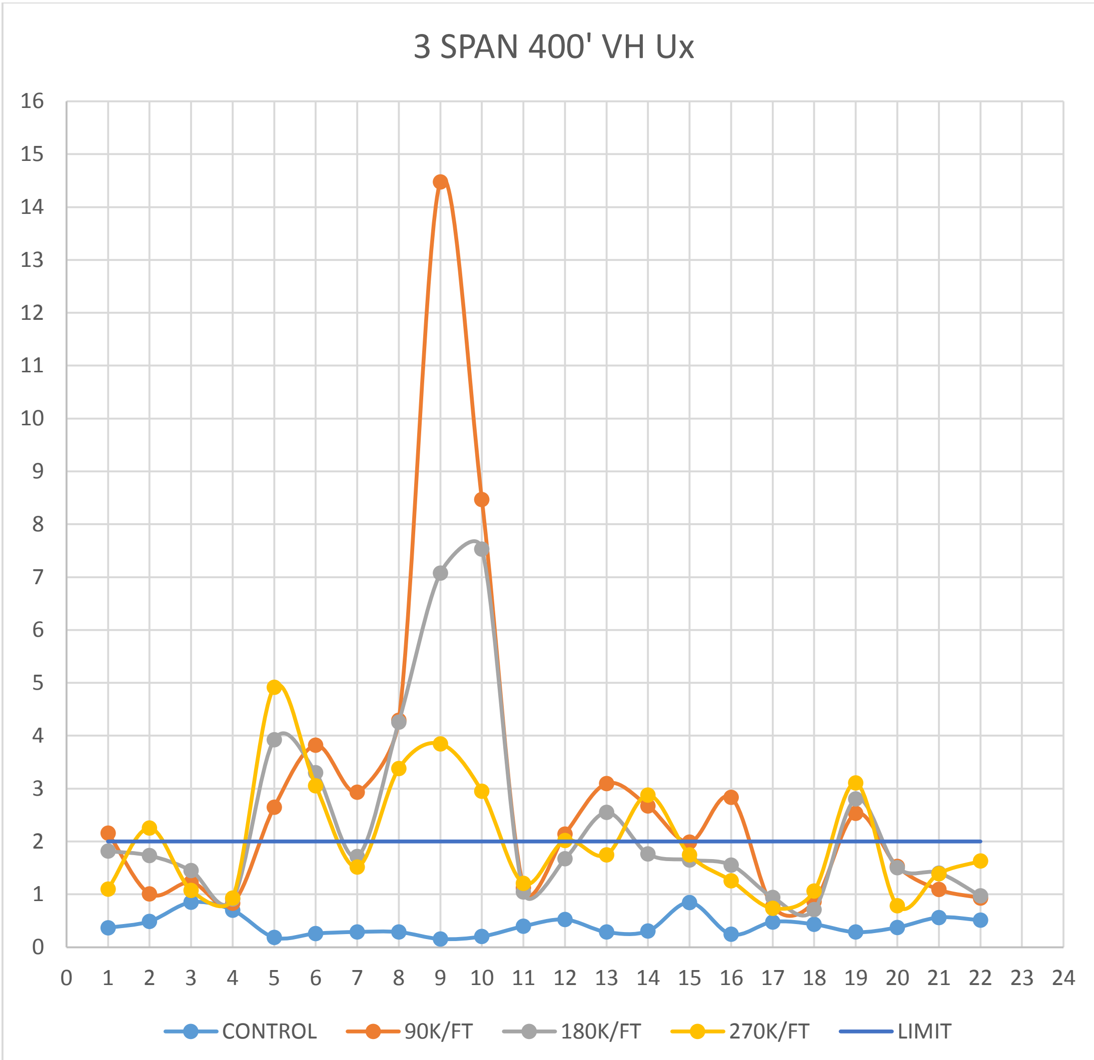


Fig. 4-47 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

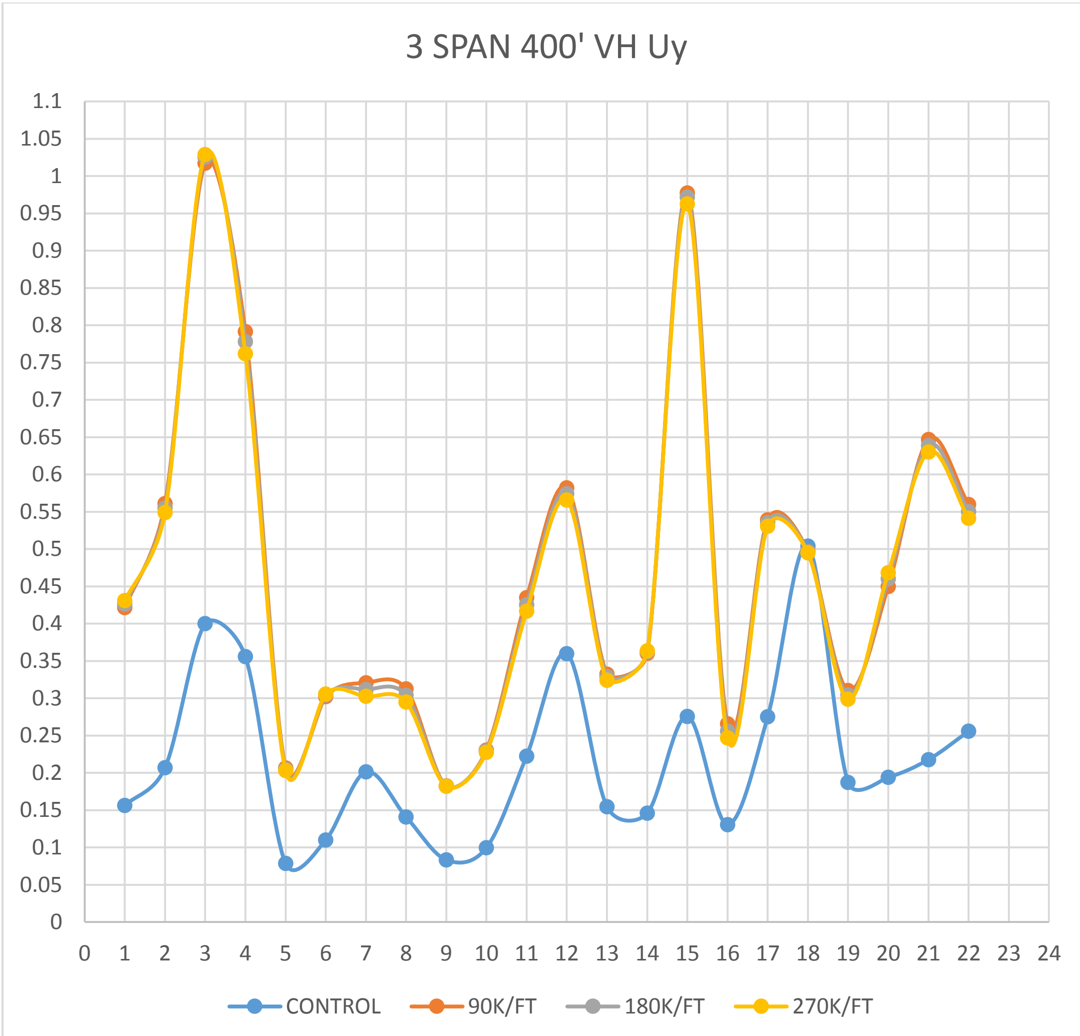


Fig. 4-48 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 20557.06

90 K/Ft = 2474.763

180 K/Ft = 2940.713

270 K/Ft = 2202.378

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

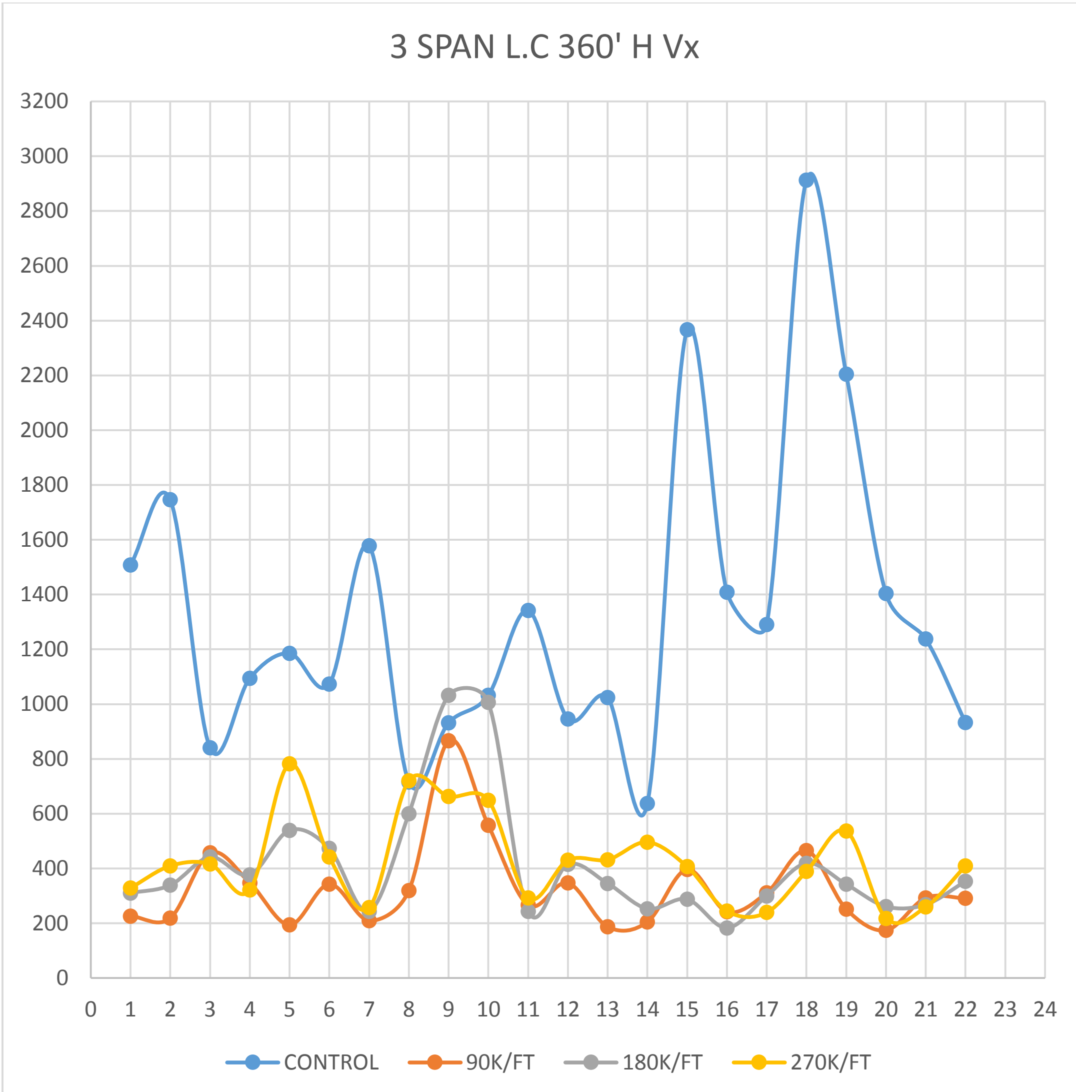


Fig. 4-49 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

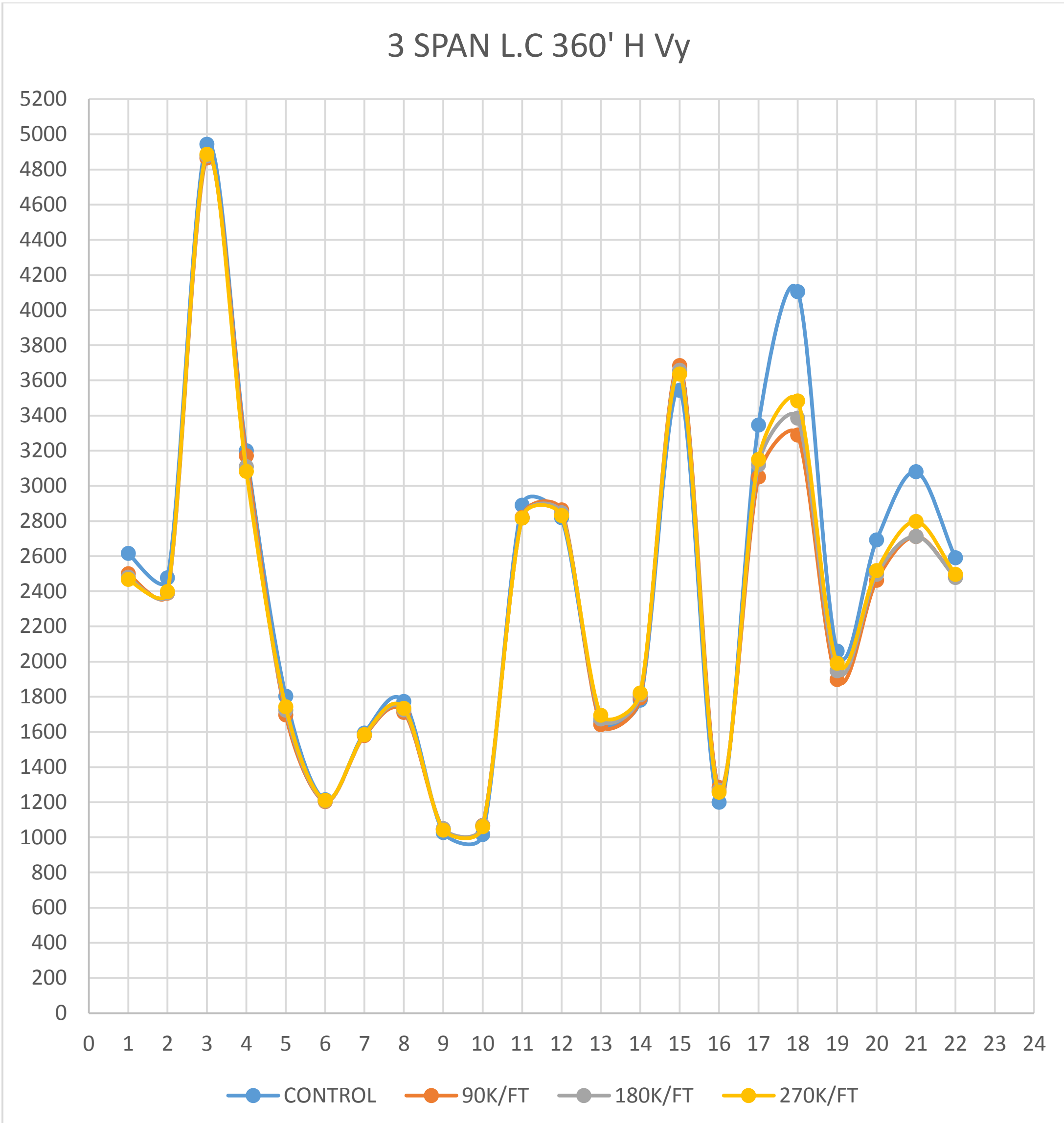


Fig. 4-50 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

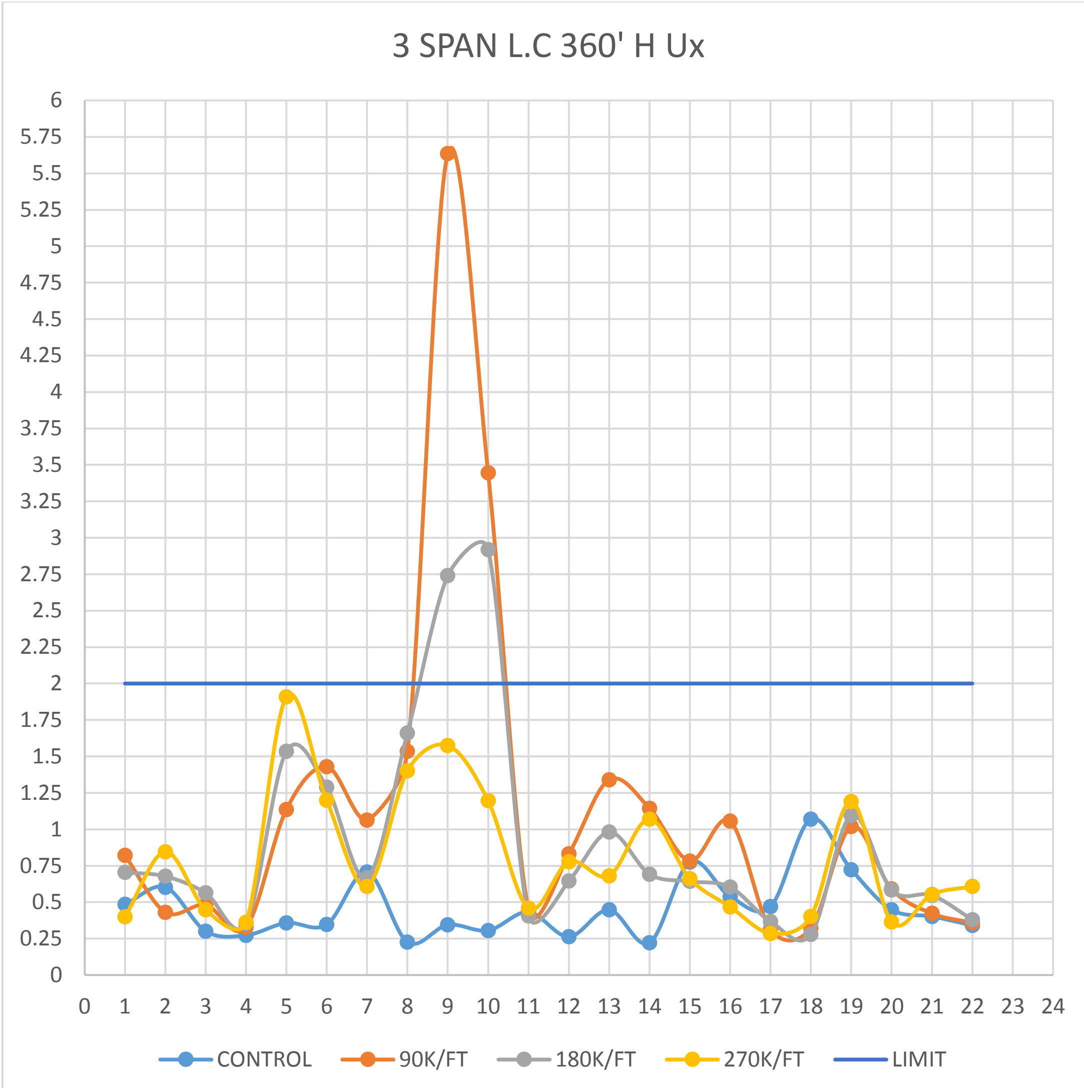


Fig. 4-51 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

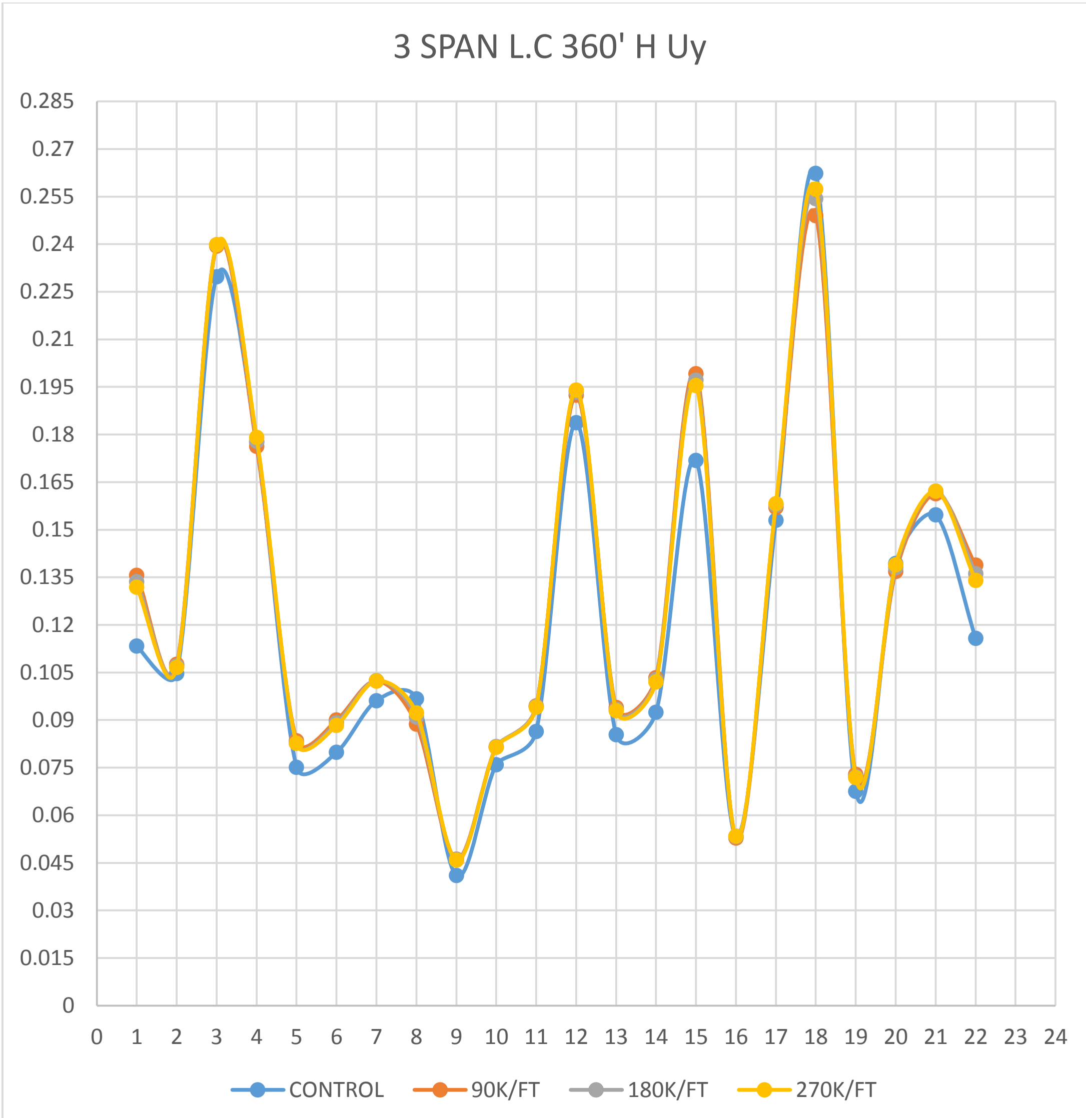


Fig. 4-52 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

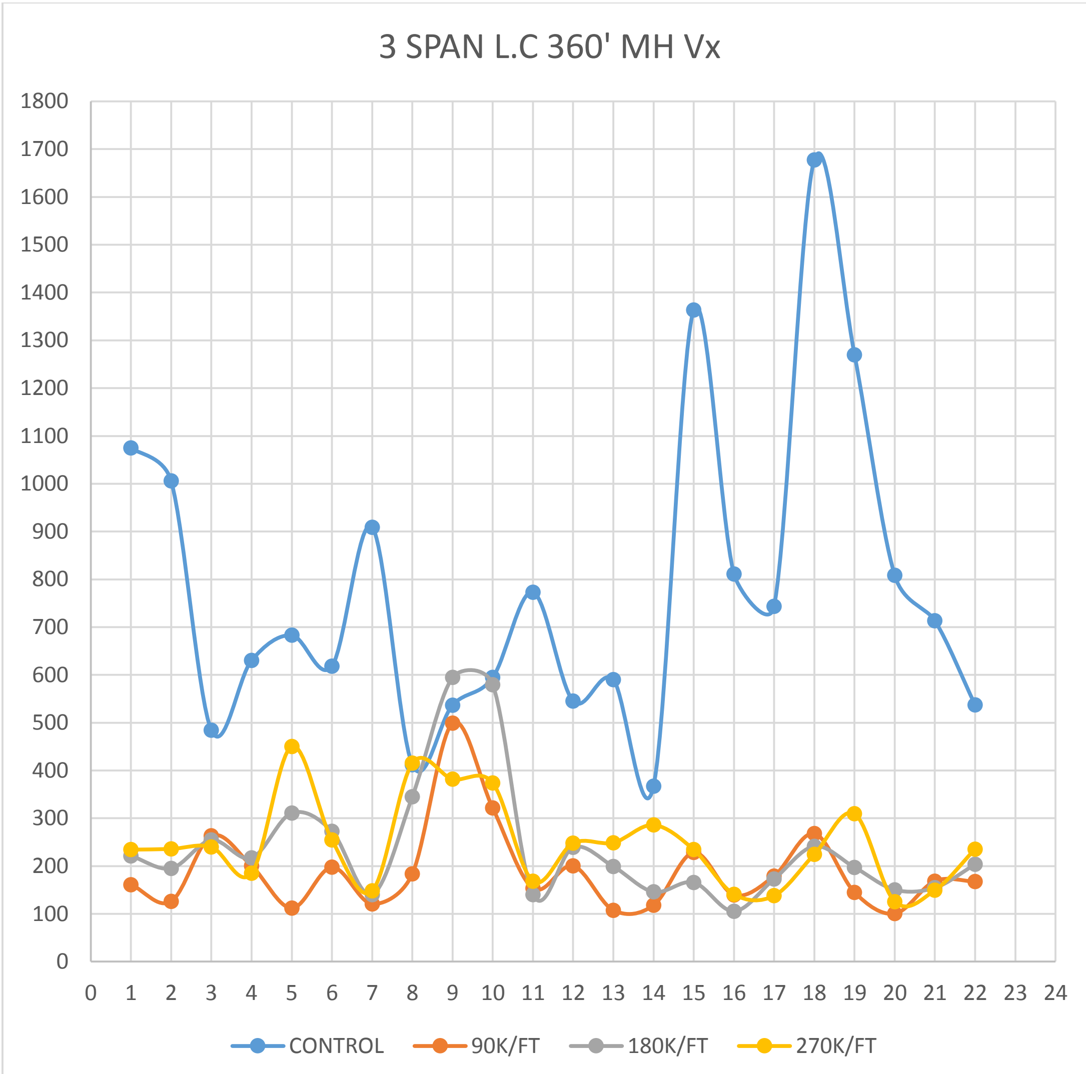


Fig. 4-53 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

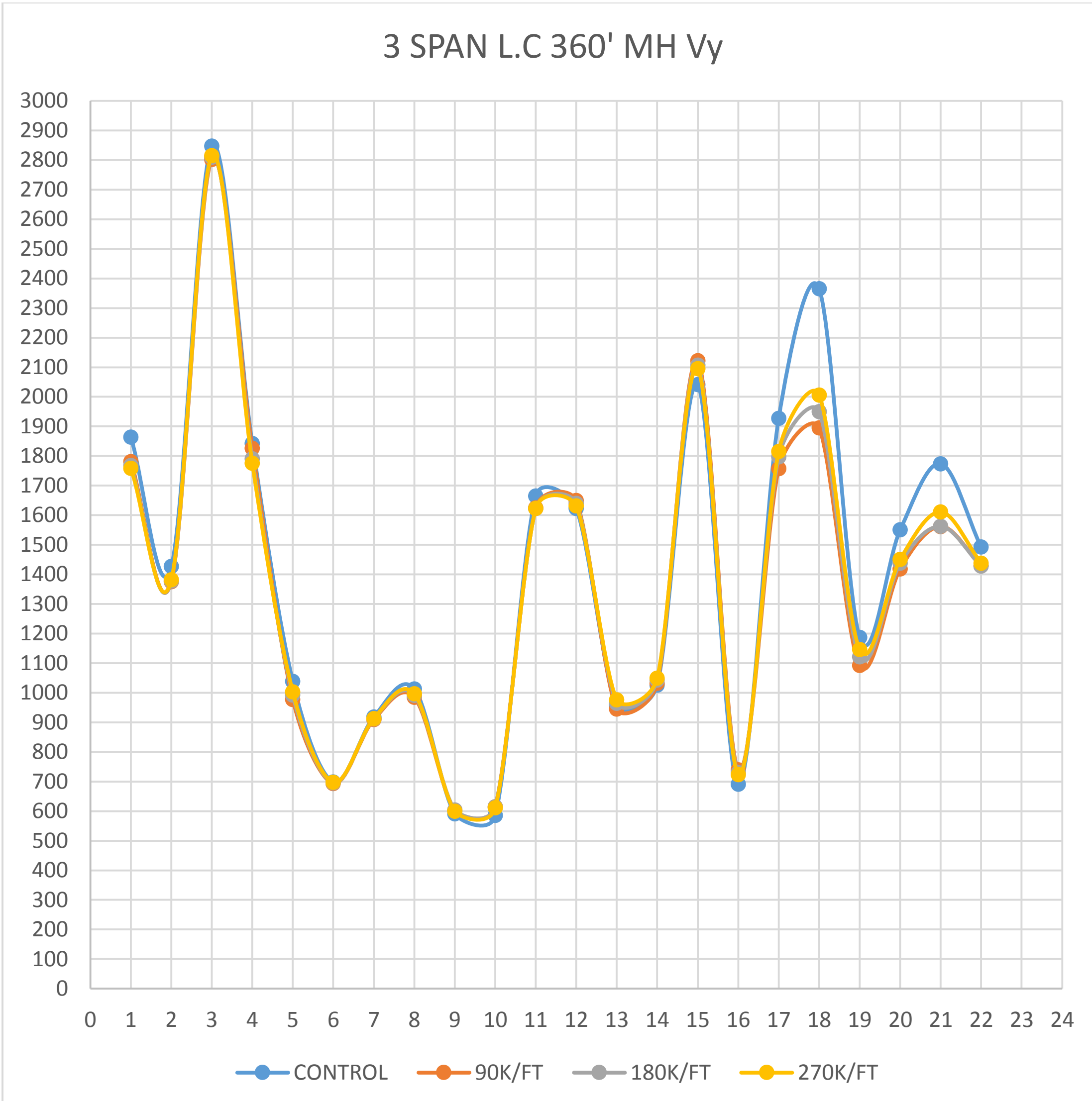


Fig. 4-54 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

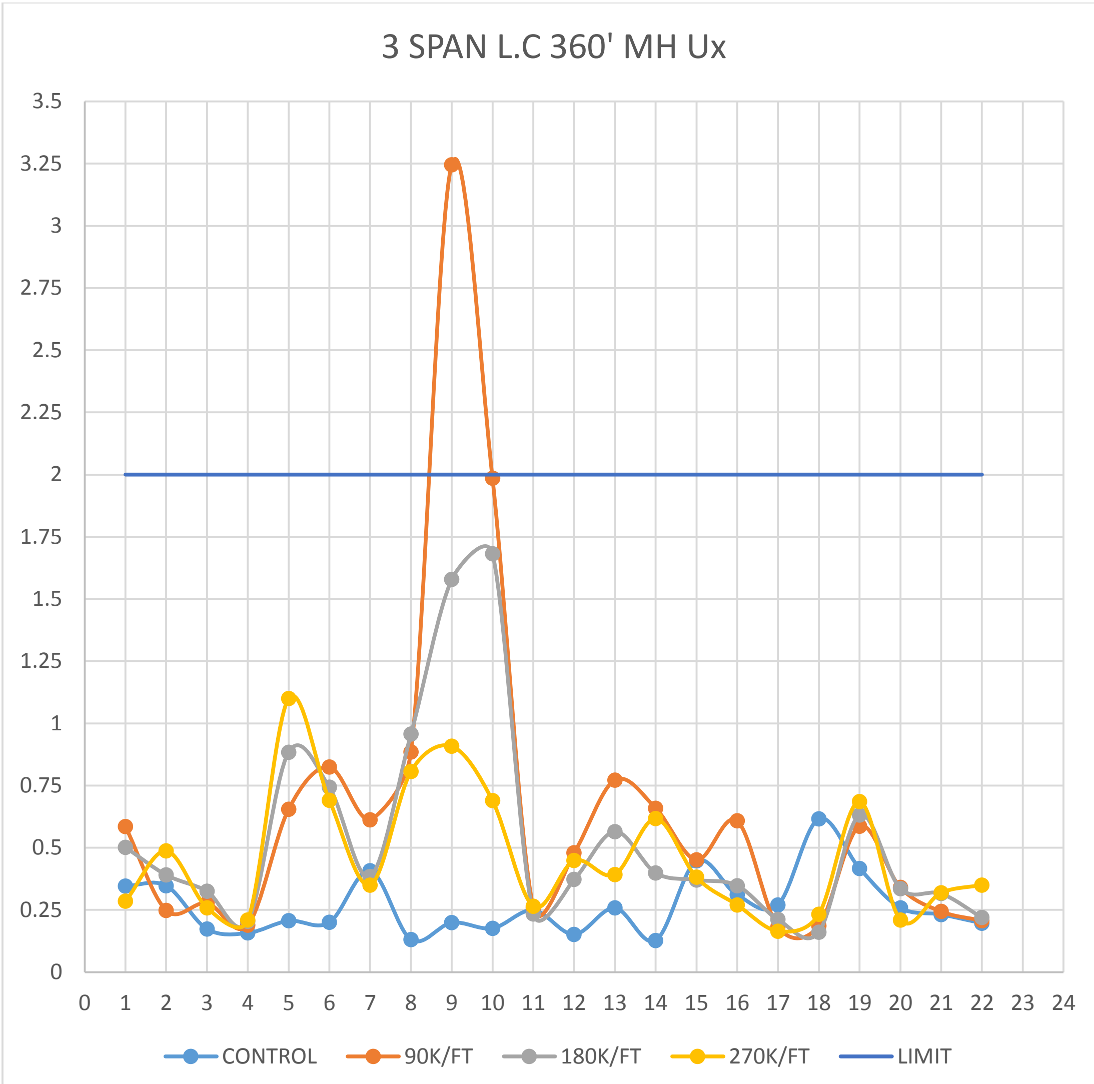


Fig. 4-55 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

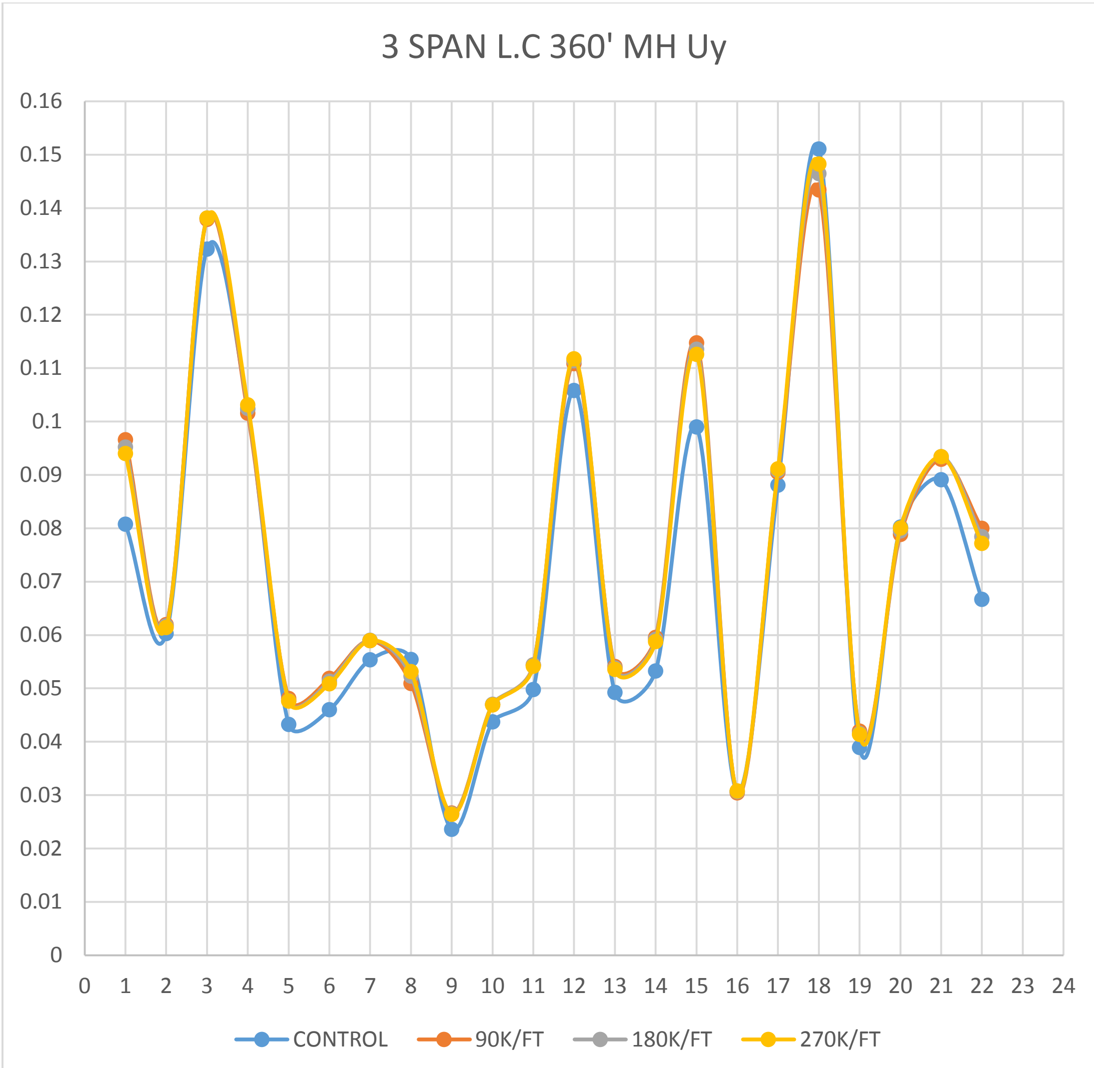


Fig. 4-56 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

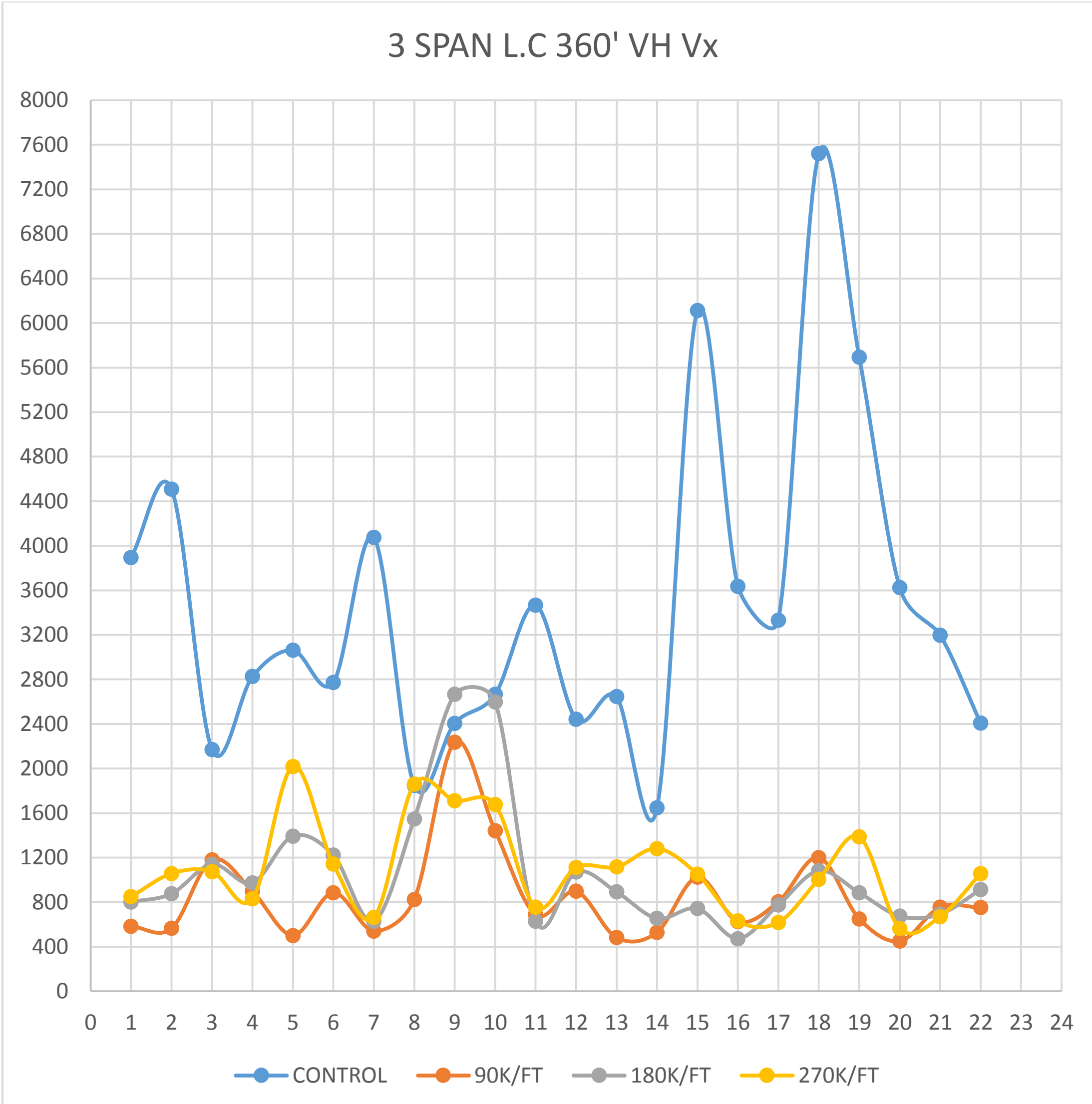


Fig. 4-57 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

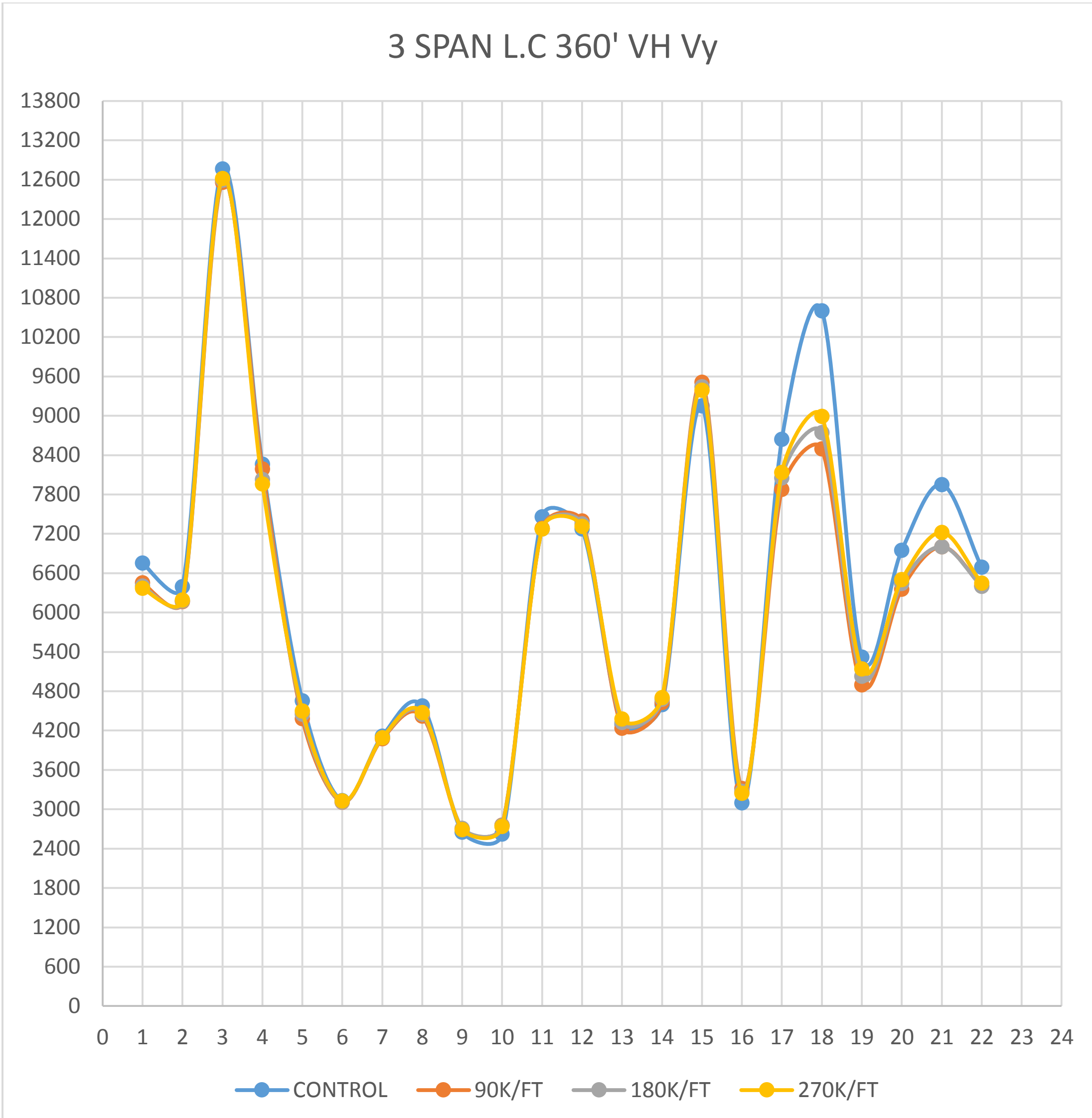


Fig. 4-58 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

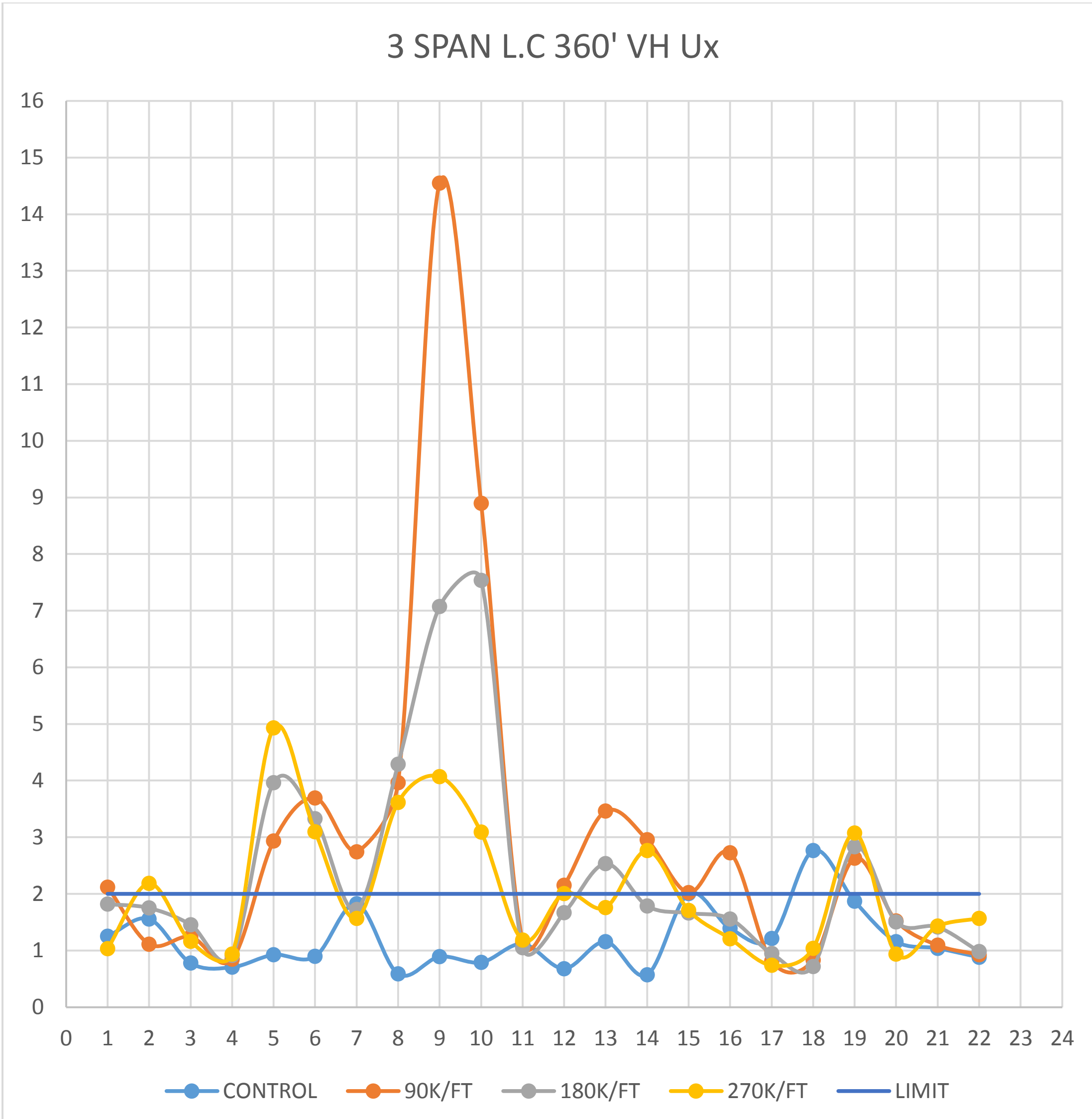


Fig. 4-59 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

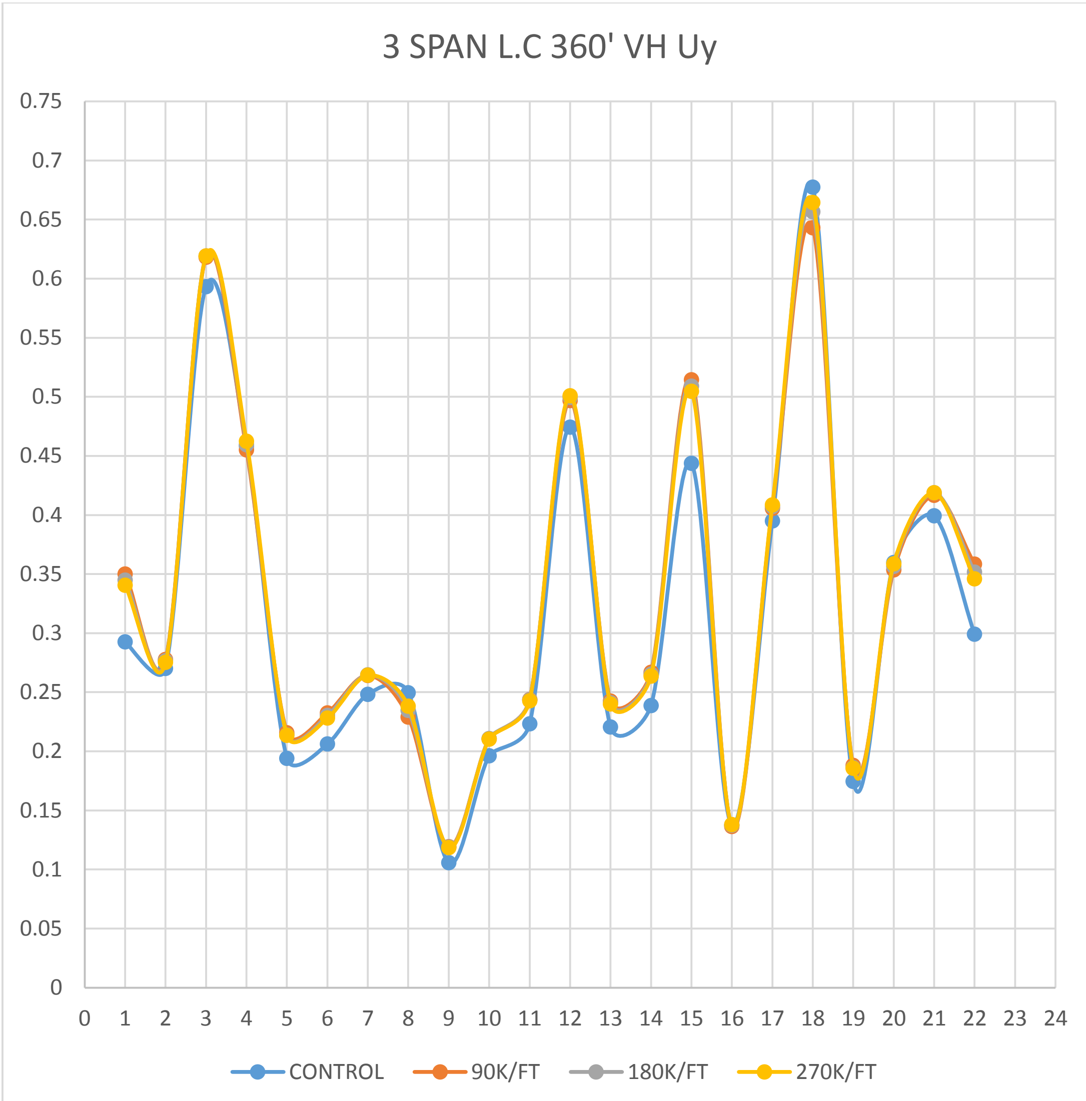


Fig. 4-60 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 7520.582

90 K/Ft = 2237.145

180 K/Ft = 2666.131

270 K/Ft = 2018.658

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

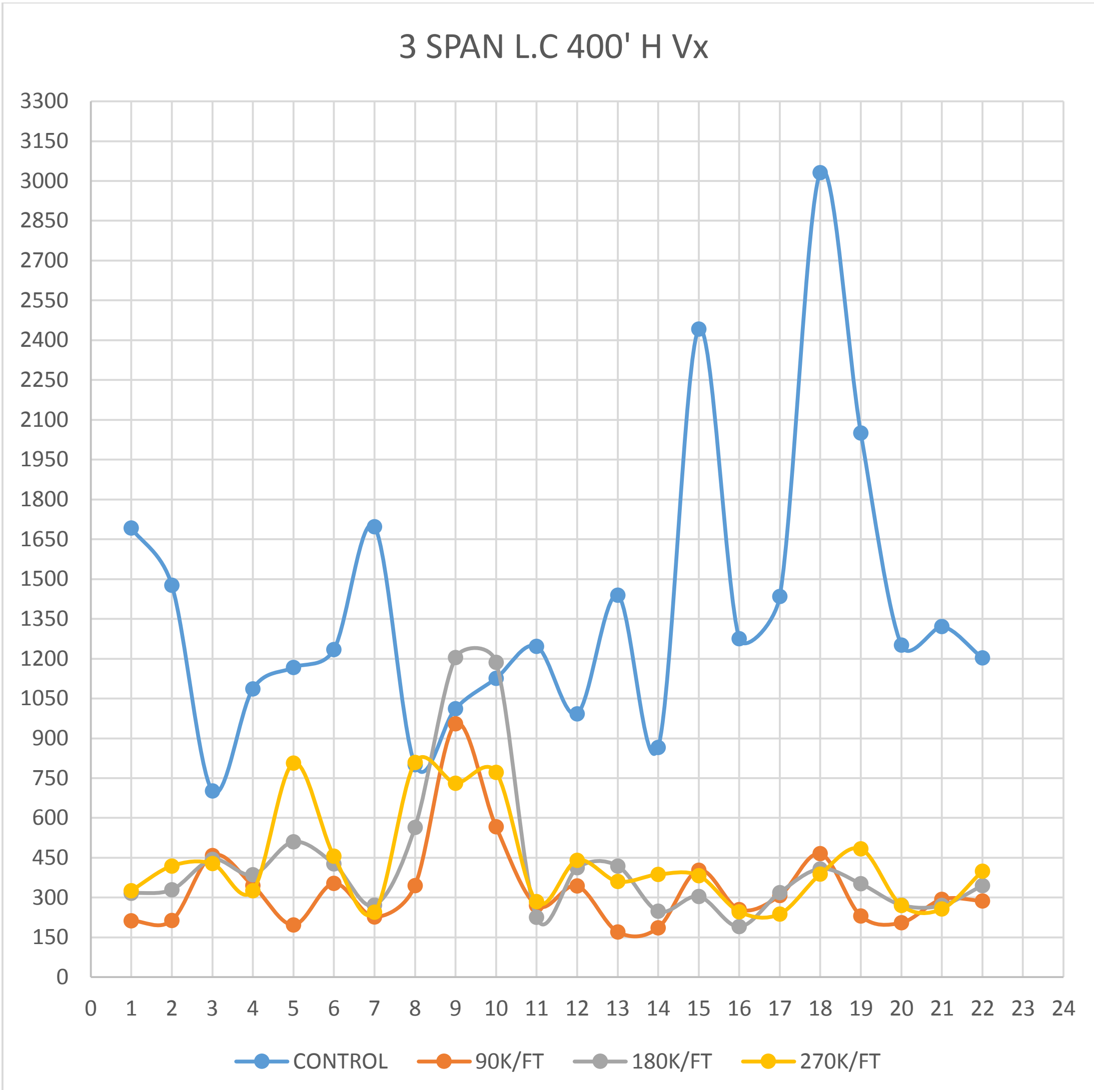


Fig. 4-61 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

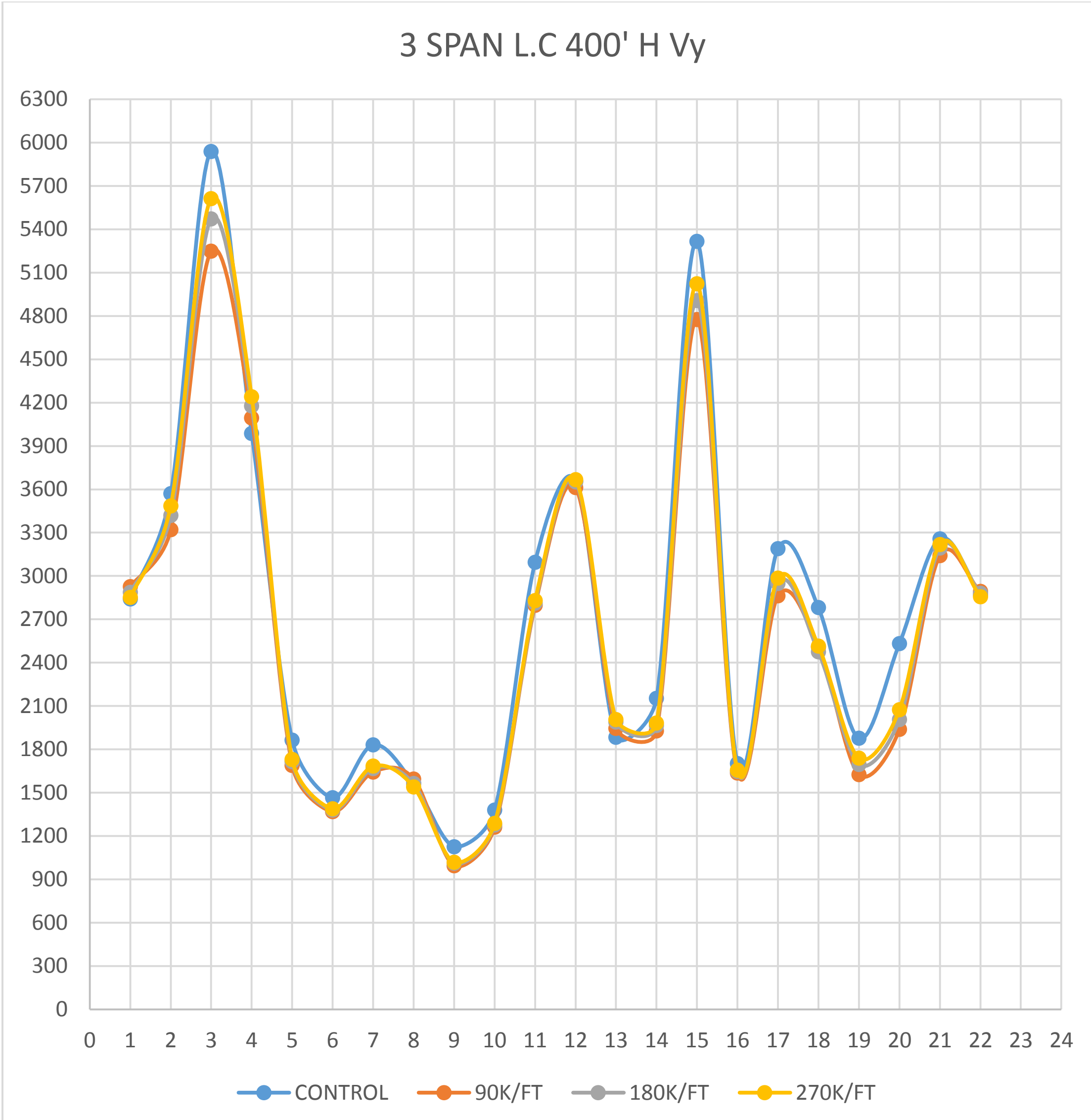


Fig. 4-62 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

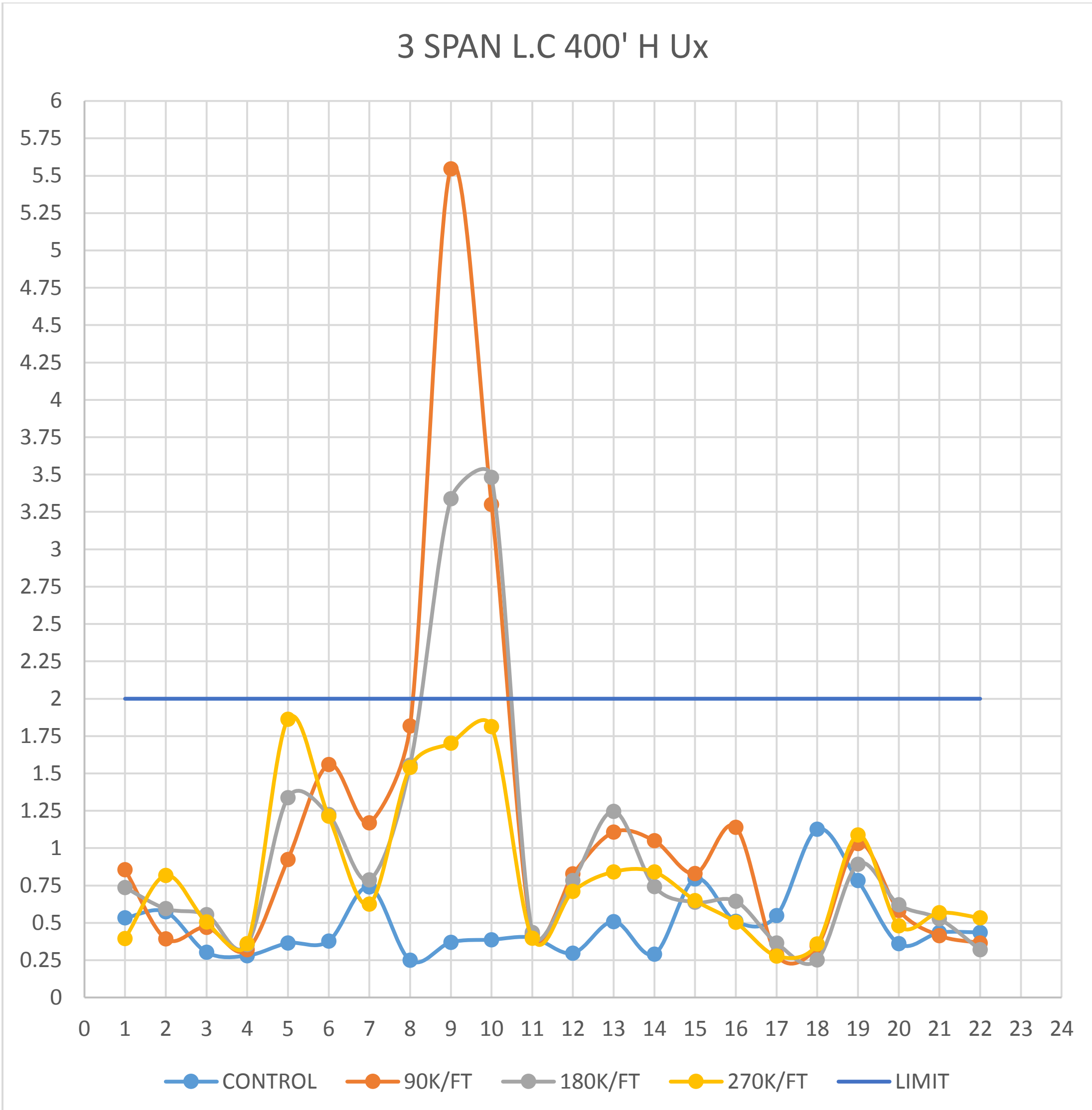


Fig. 4-63 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

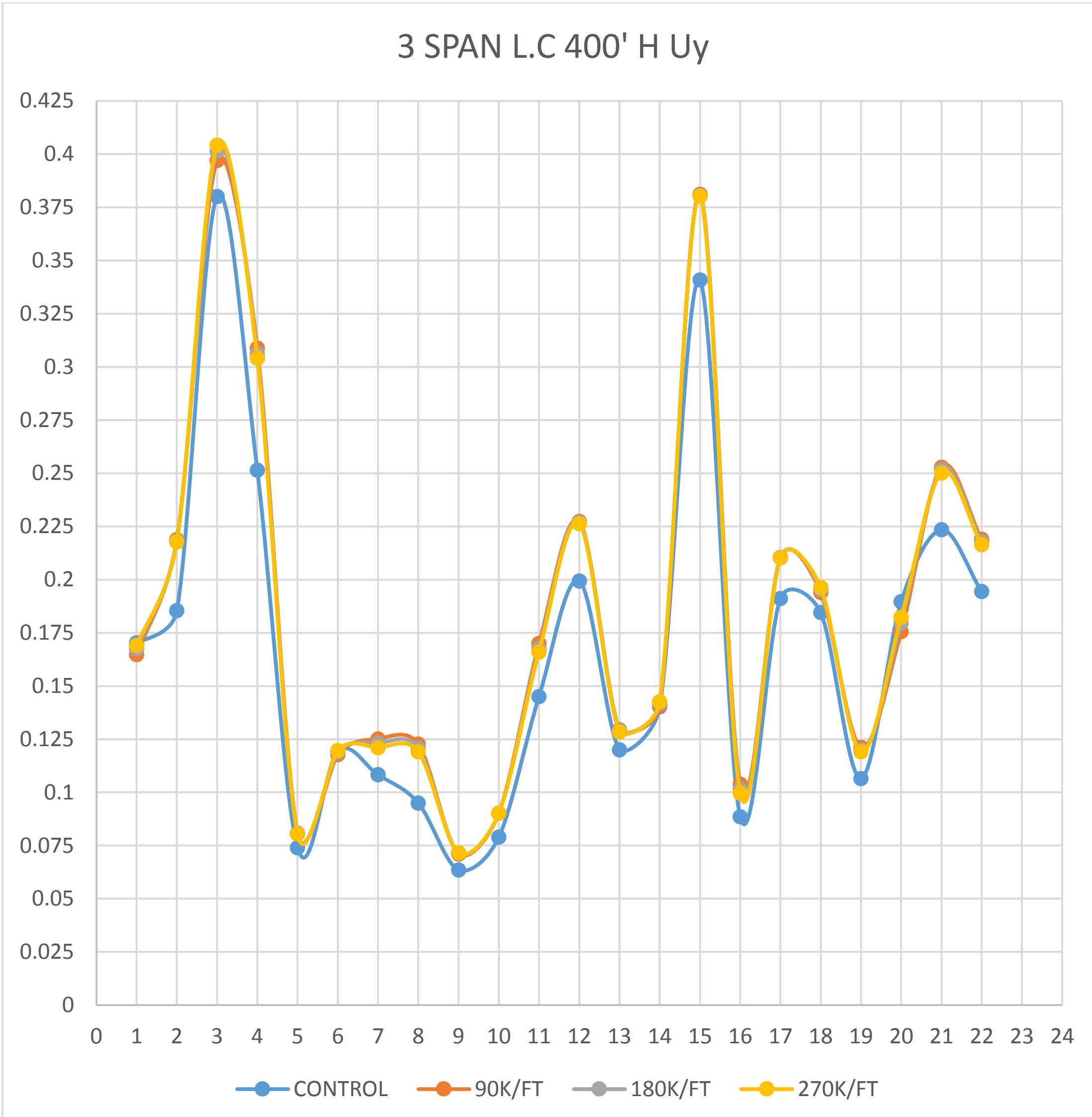


Fig. 4-64 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the three span bridge.

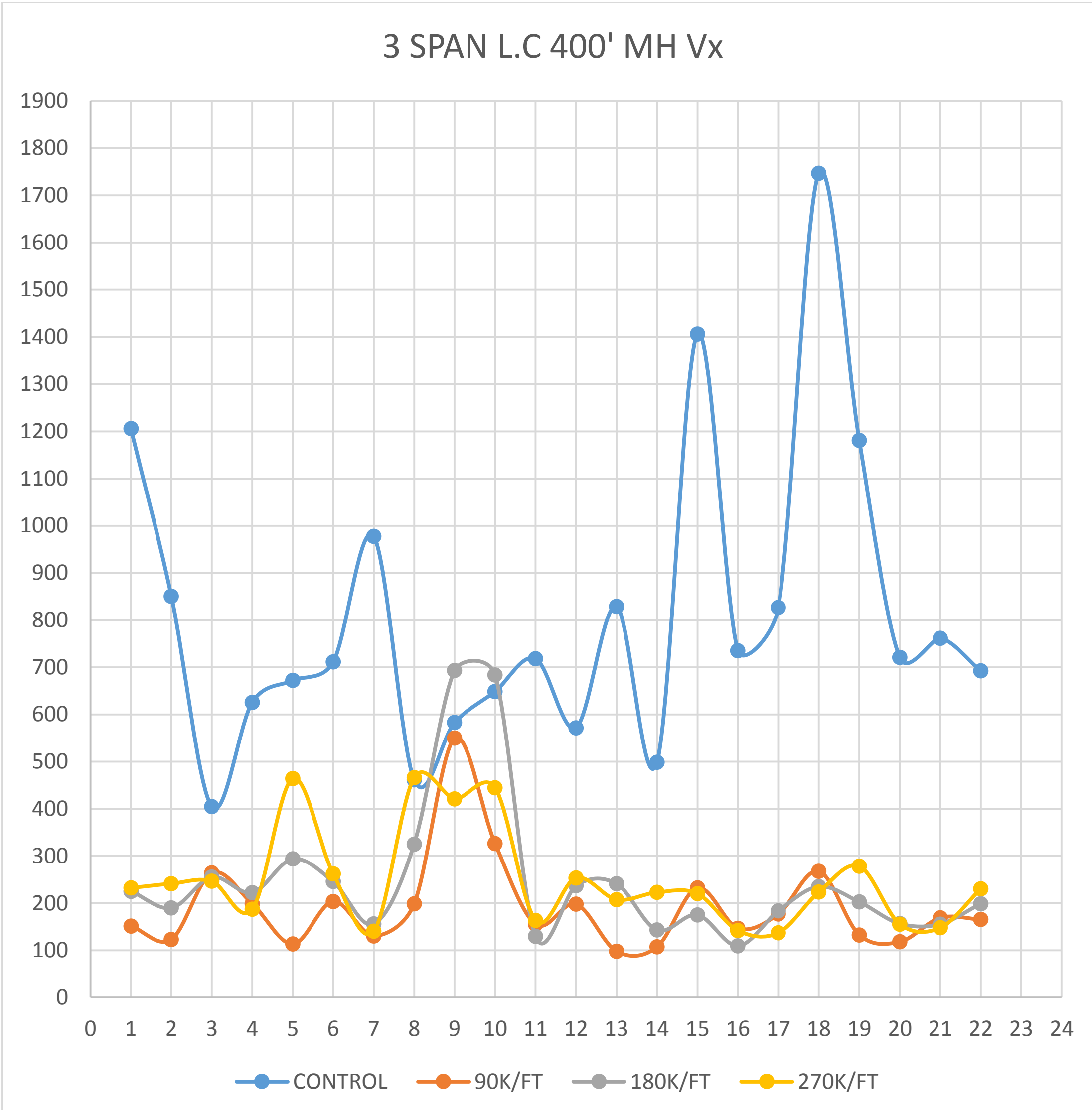


Fig. 4-65 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

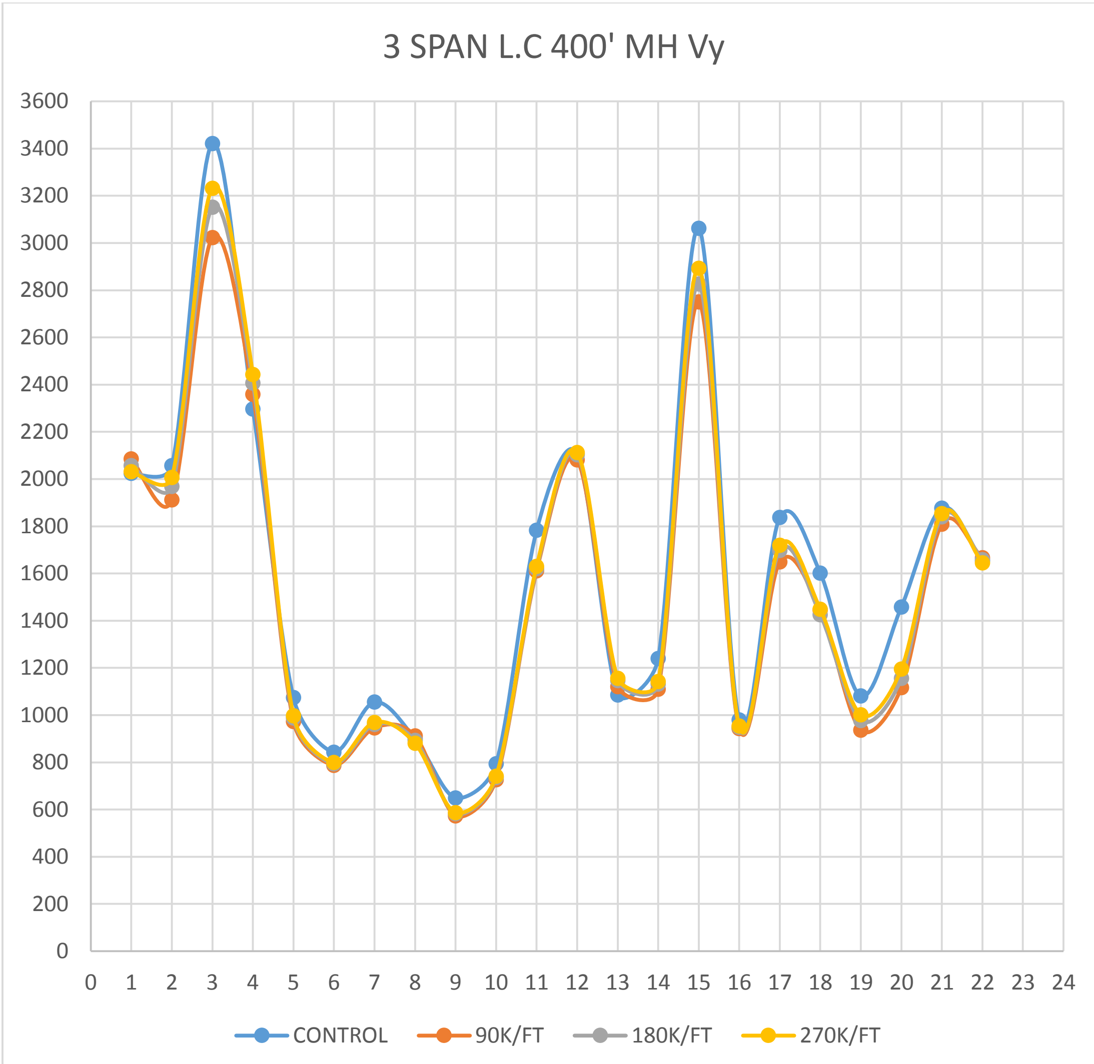


Fig. 4-66 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

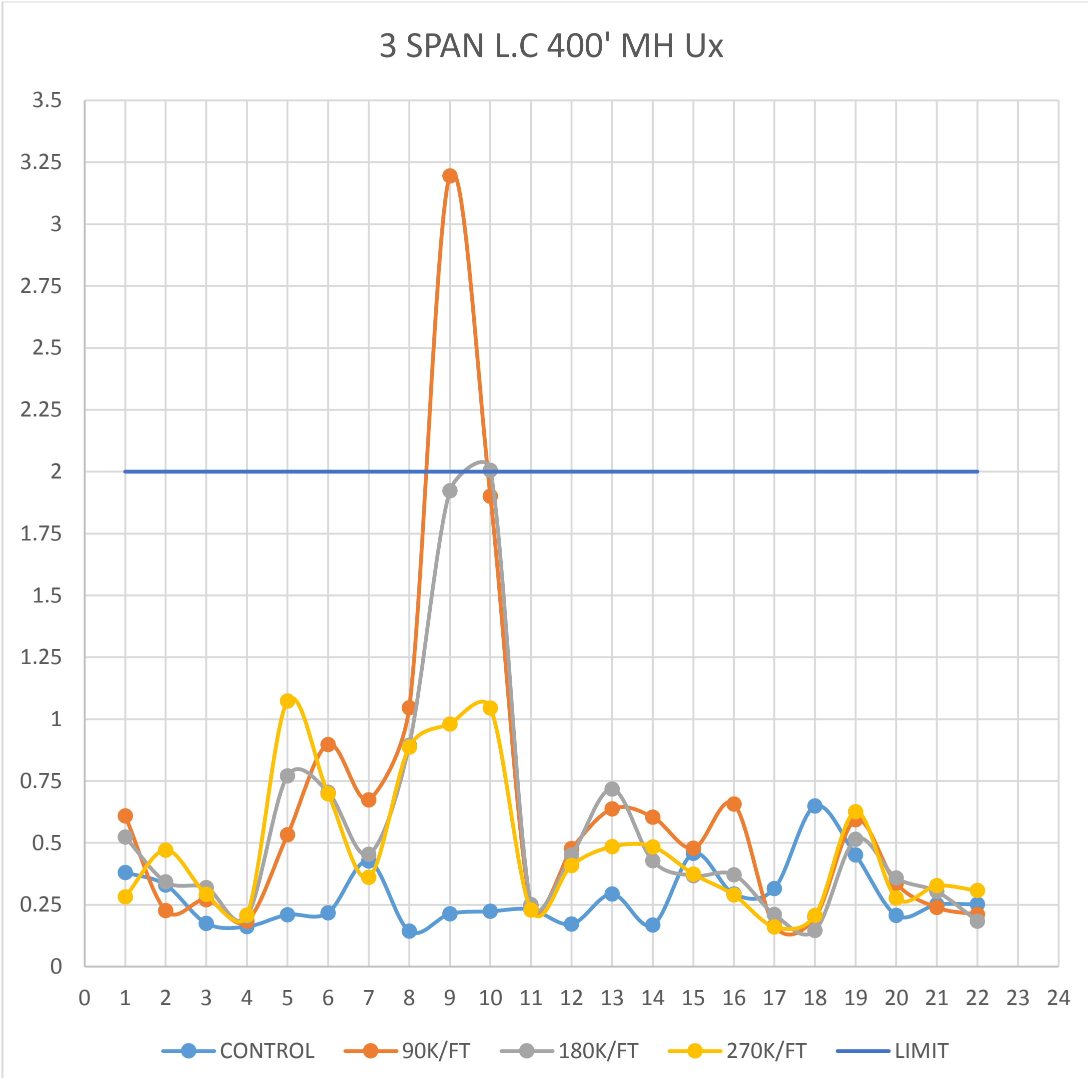


Fig. 4-67 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

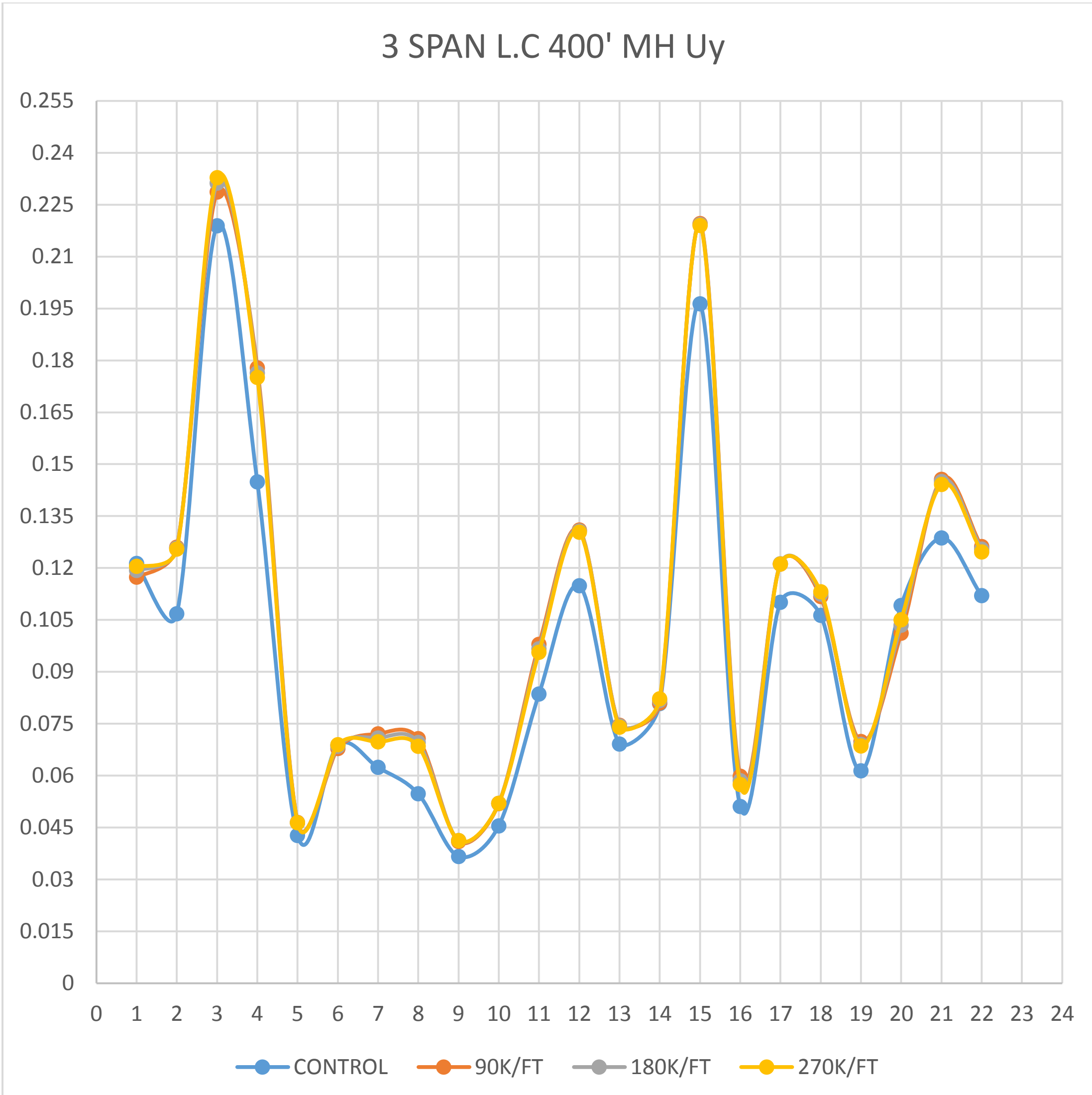


Fig. 4-68 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the three span bridge.

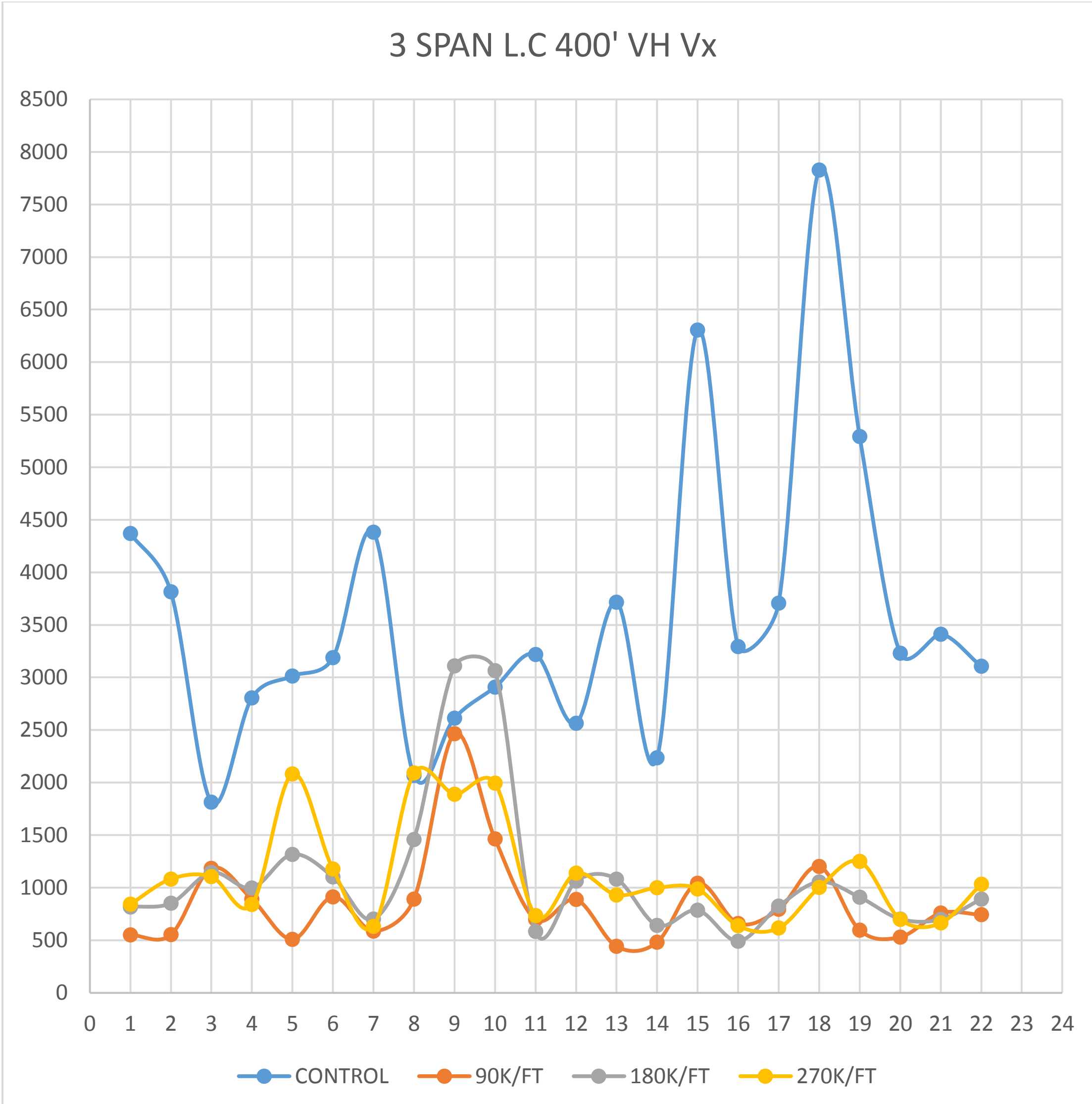


Fig. 4-69 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

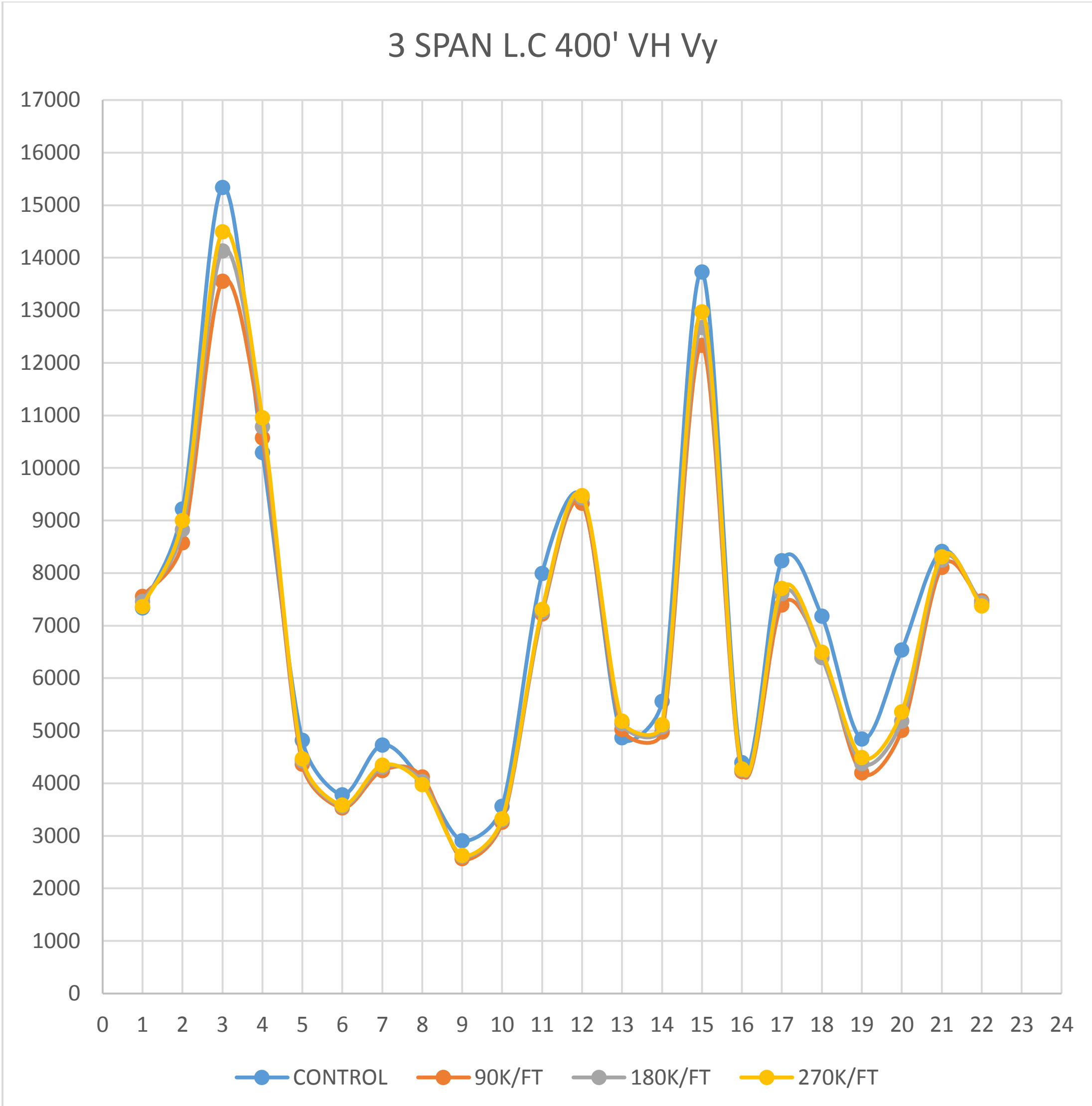


Fig. 4-70 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

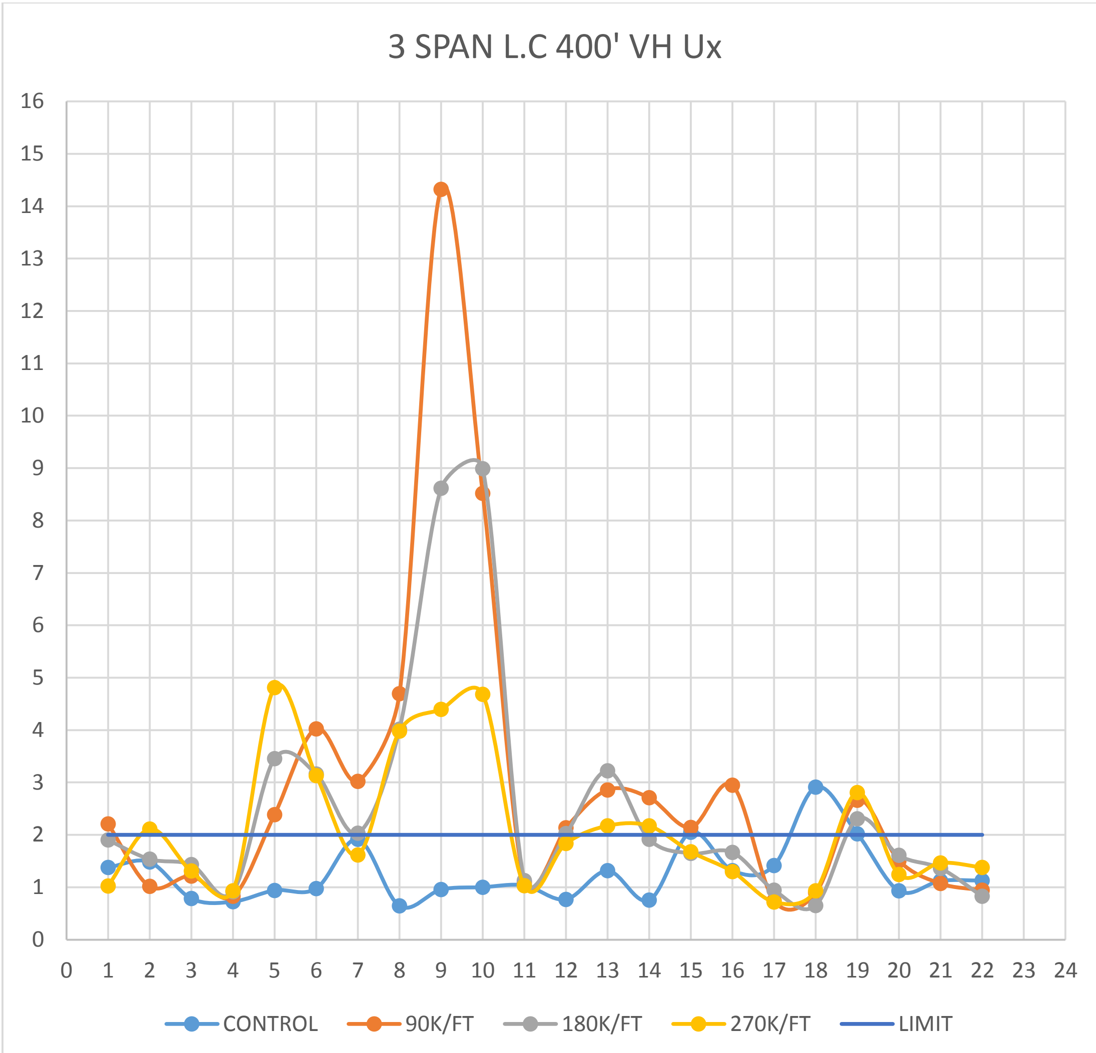


Fig. 4-71 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

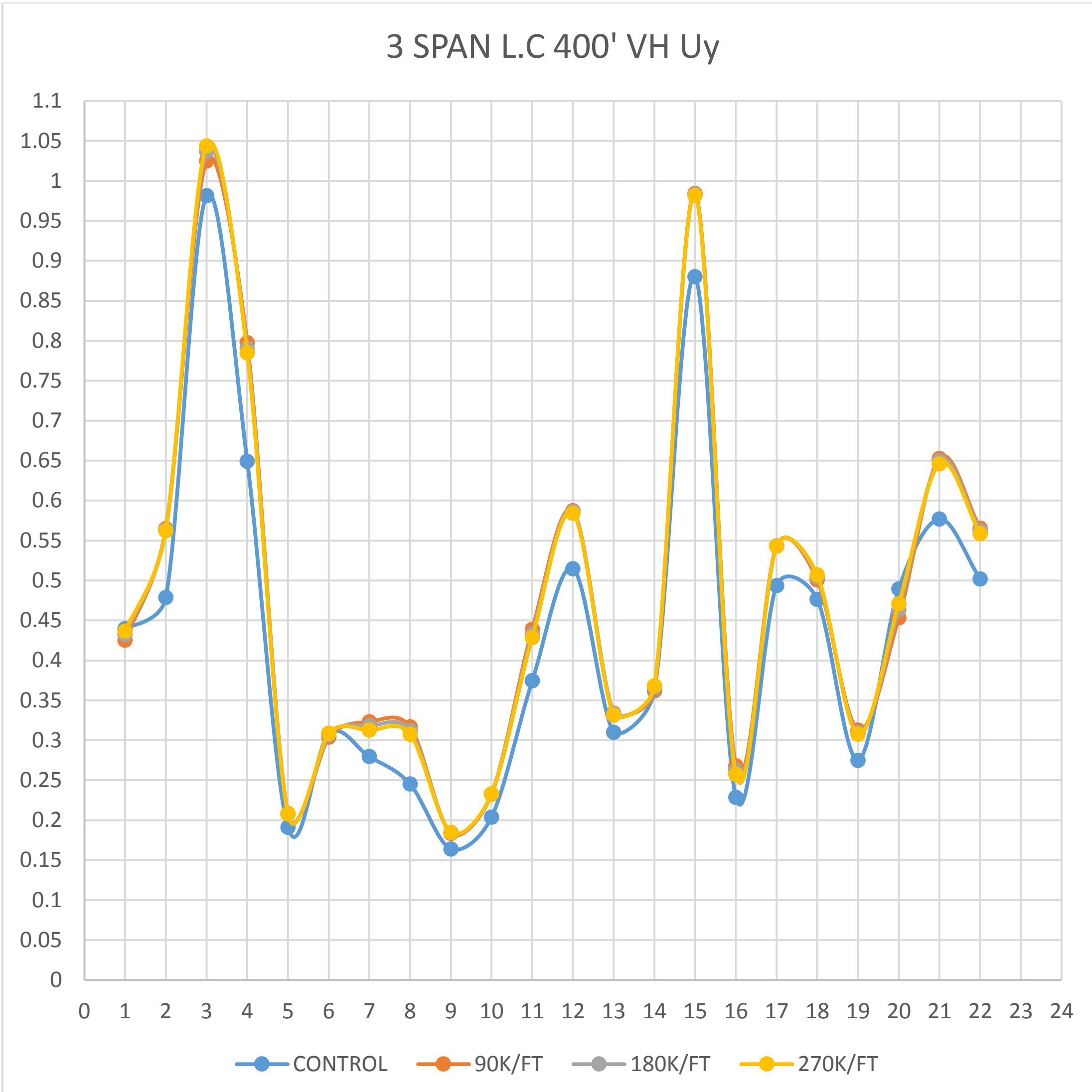


Fig. 4-72 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the three span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 3 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 3 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 3 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 7829.442

90 K/Ft = 2464.082

180 K/Ft = 3108.629

270 K/Ft = 2089.676

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

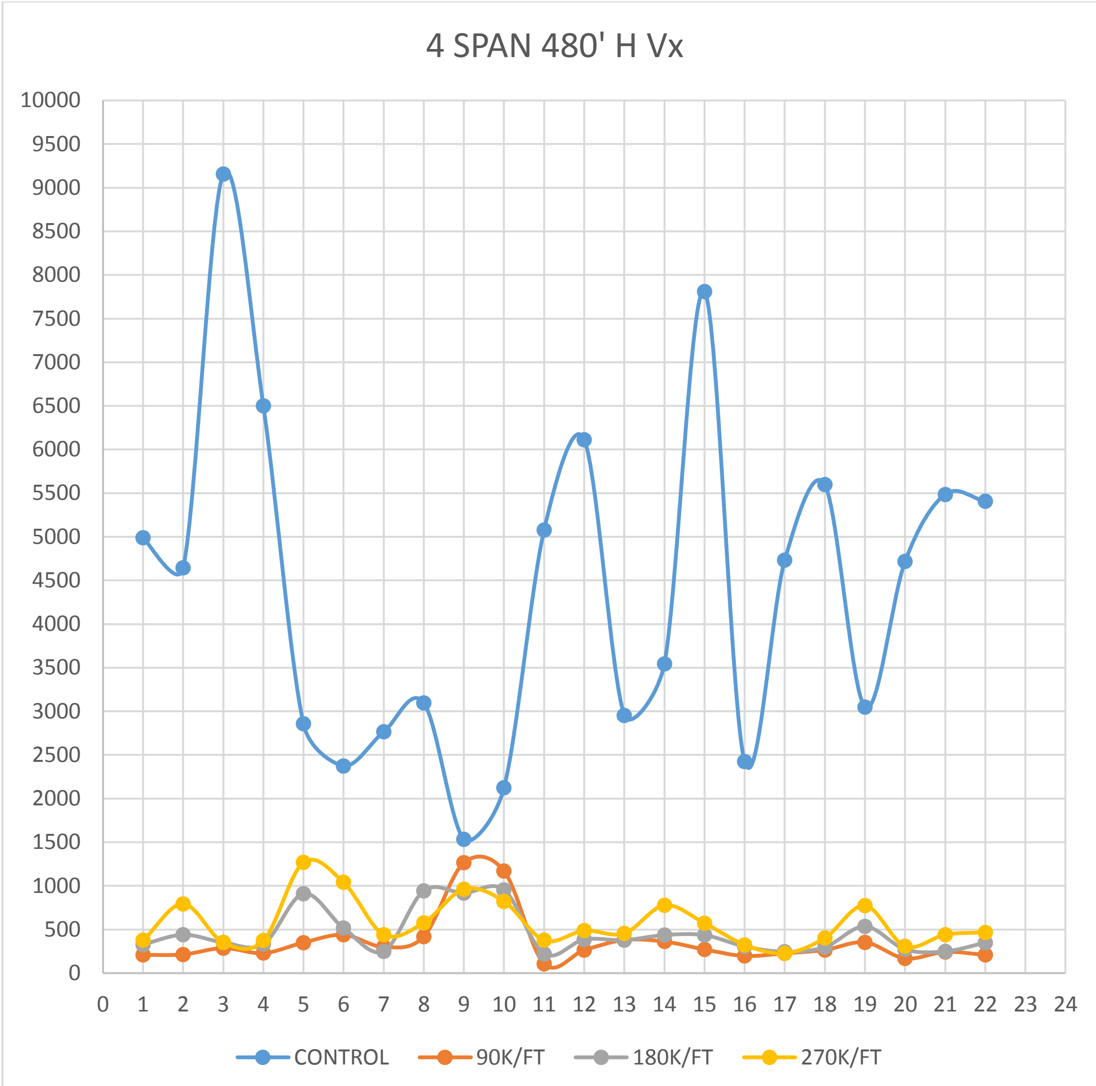


Fig. 4-73 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

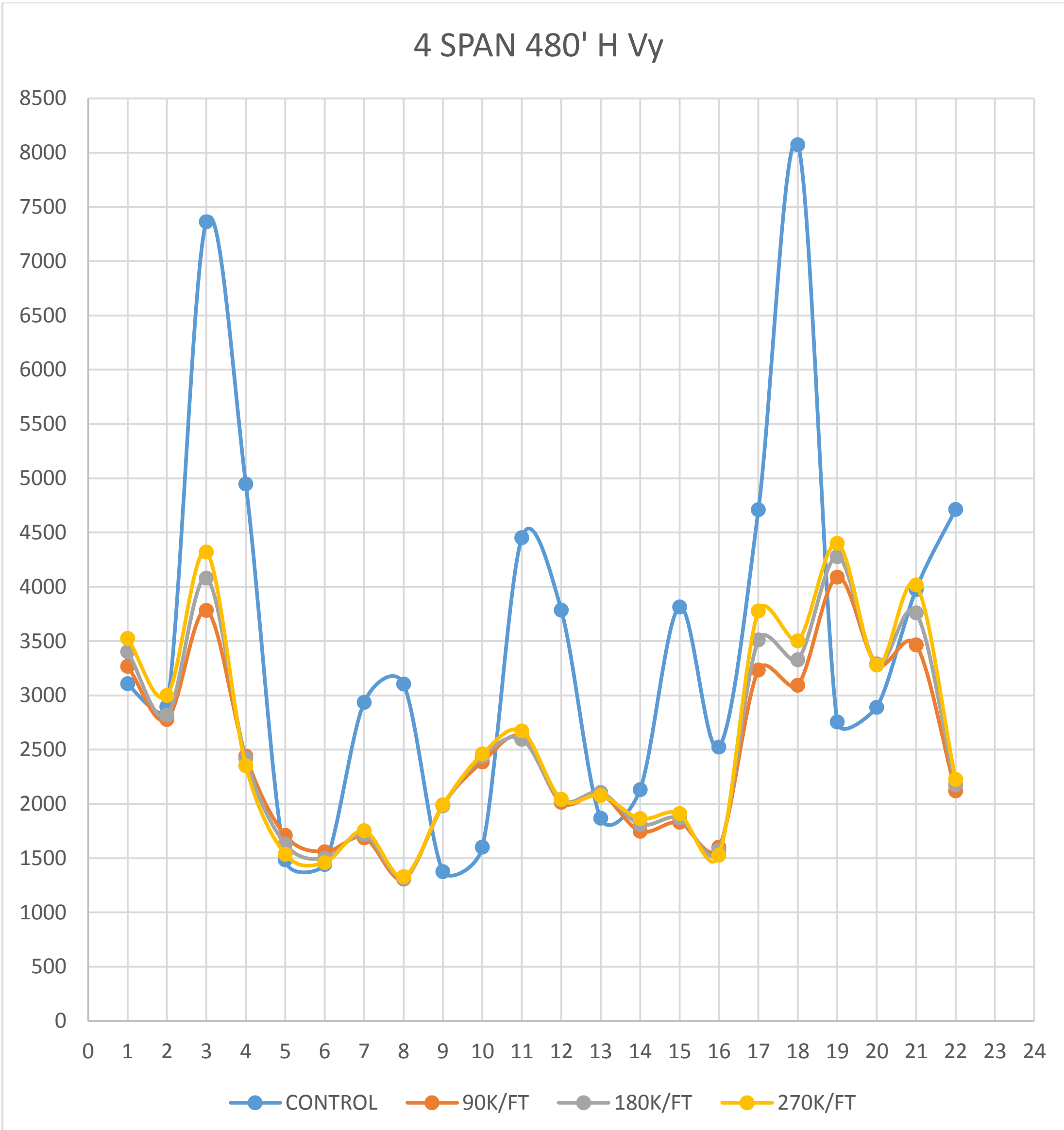


Fig. 4-74 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

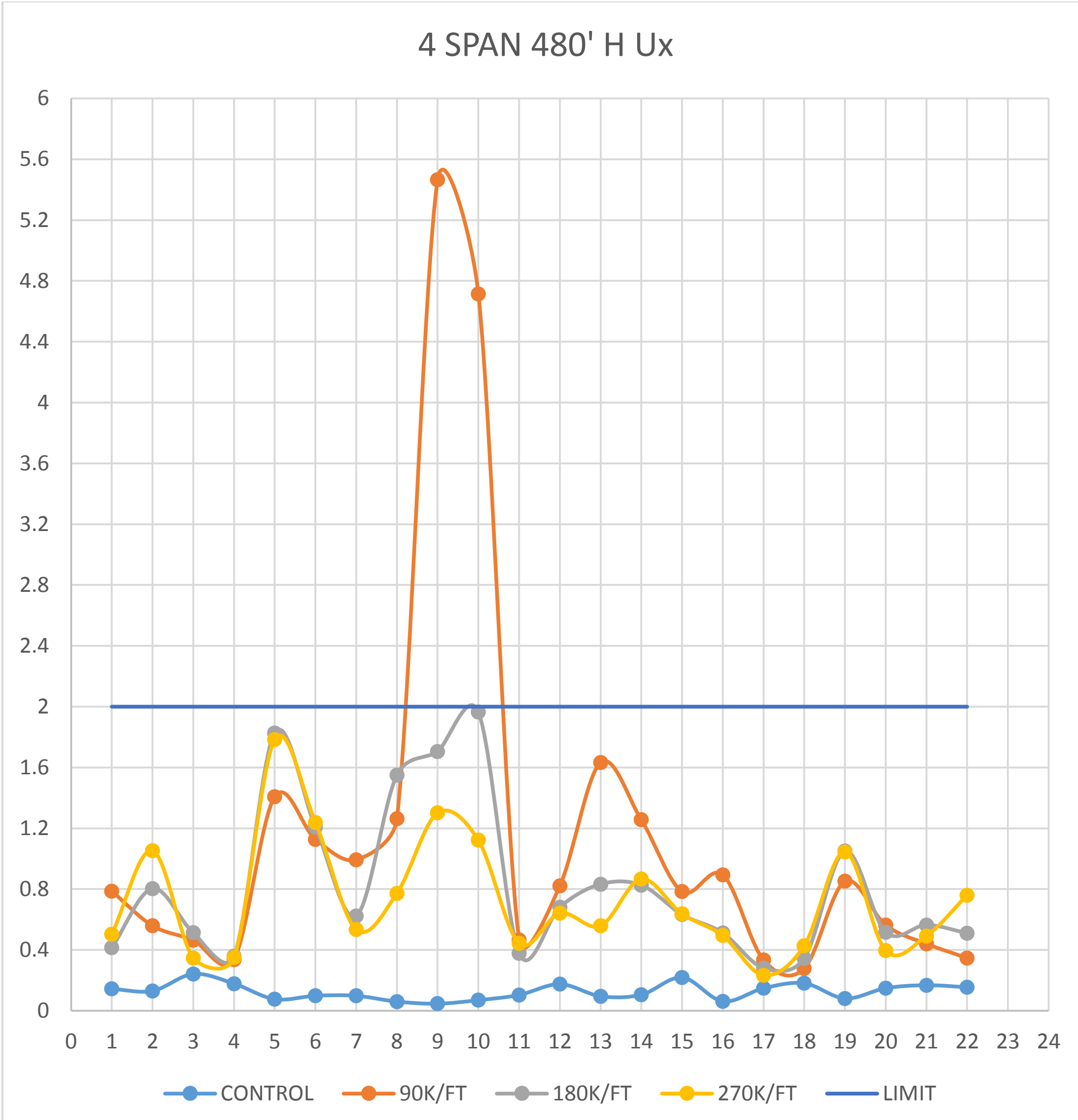


Fig. 4-75 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

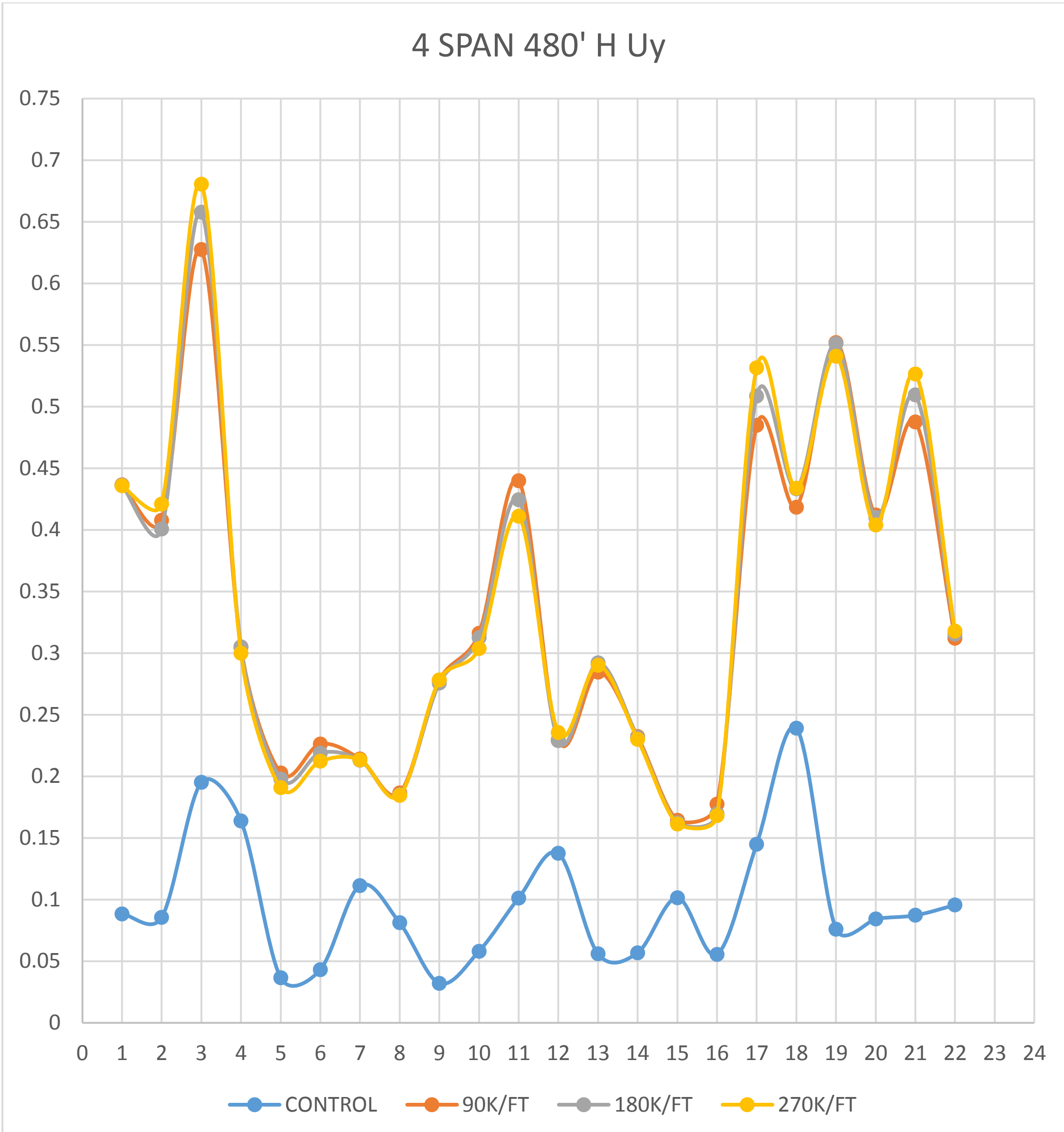


Fig. 4-76 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

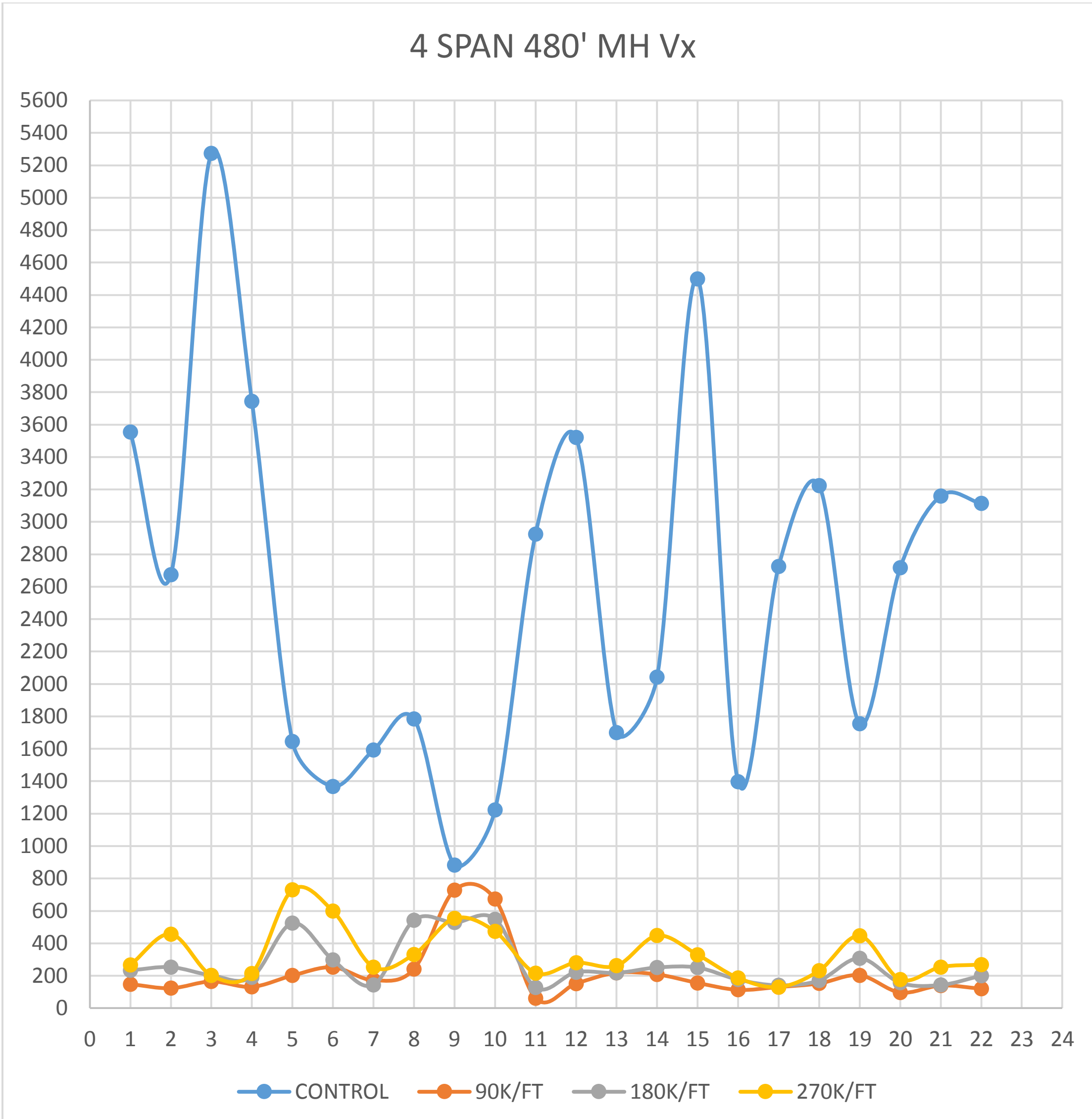


Fig. 4-77 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

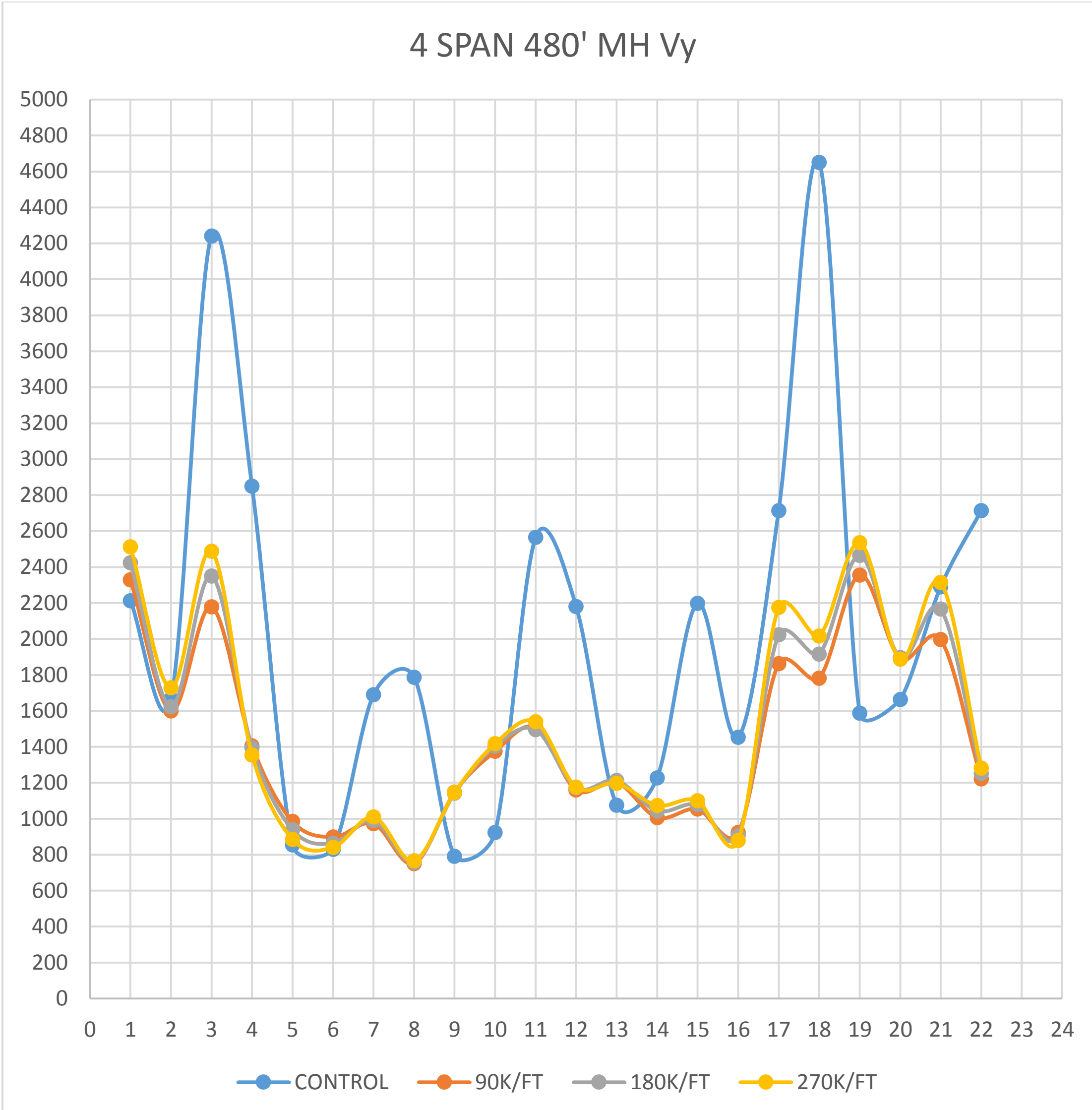


Fig. 4-78 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

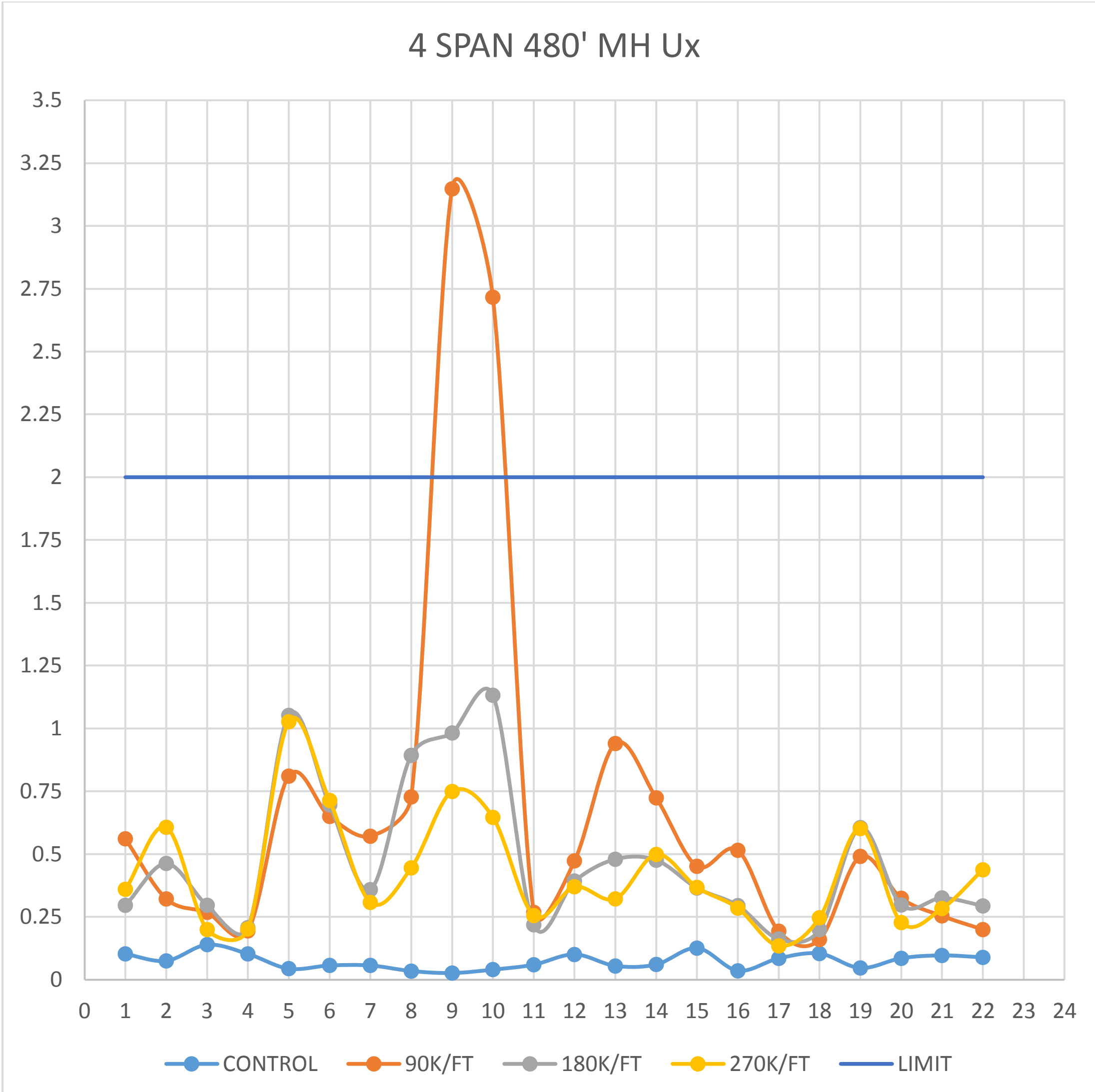


Fig. 4-79 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

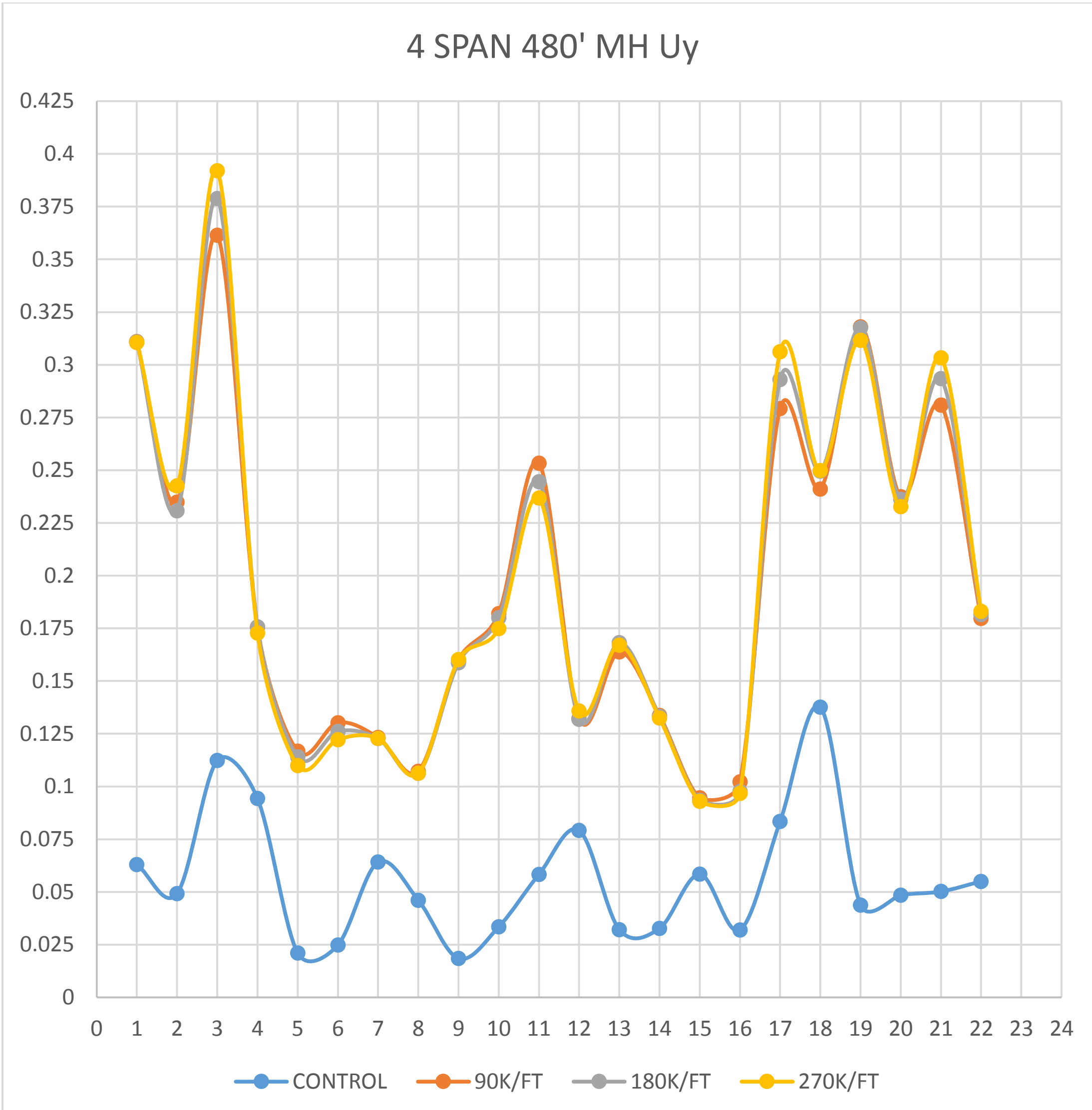


Fig. 4-80 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

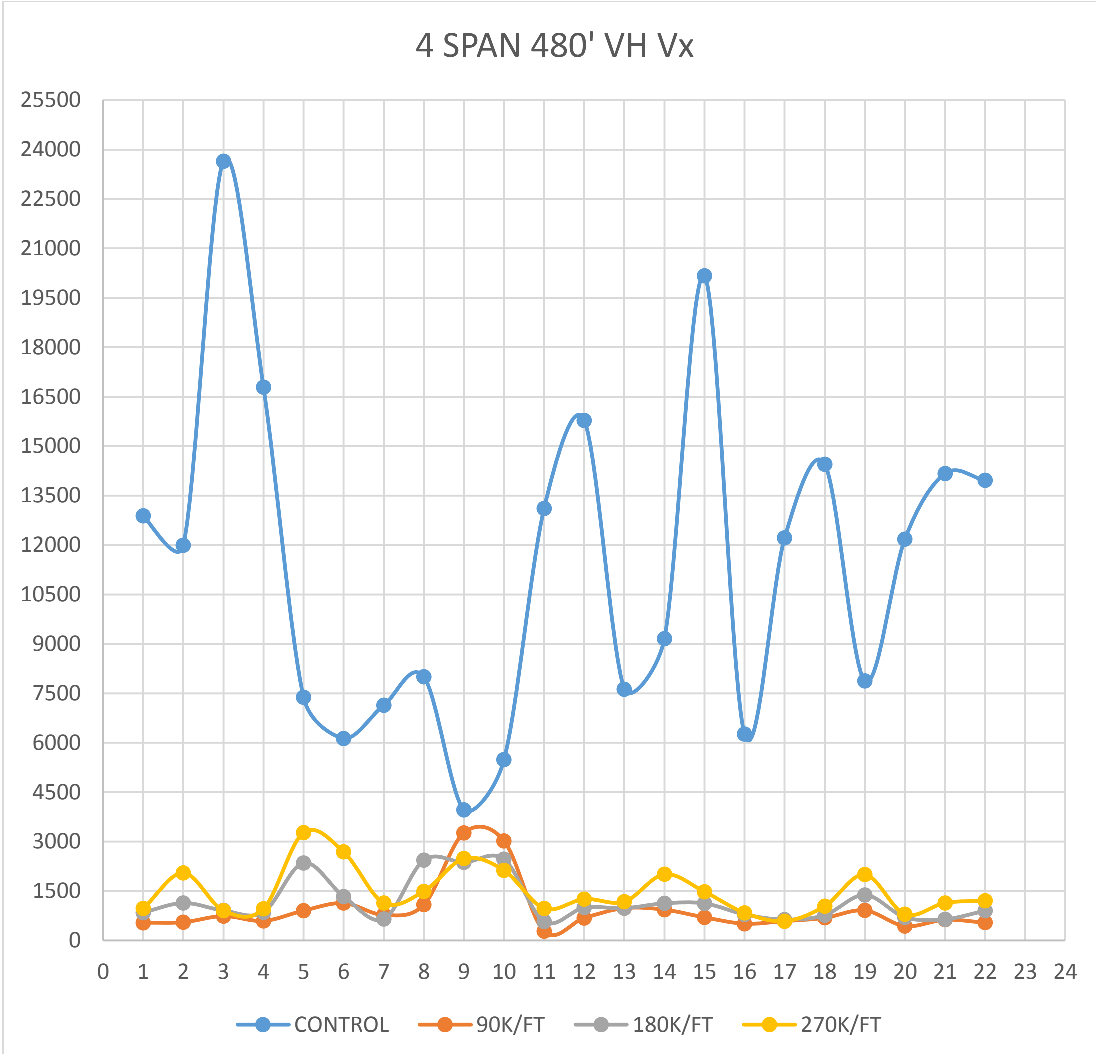


Fig. 4-81 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

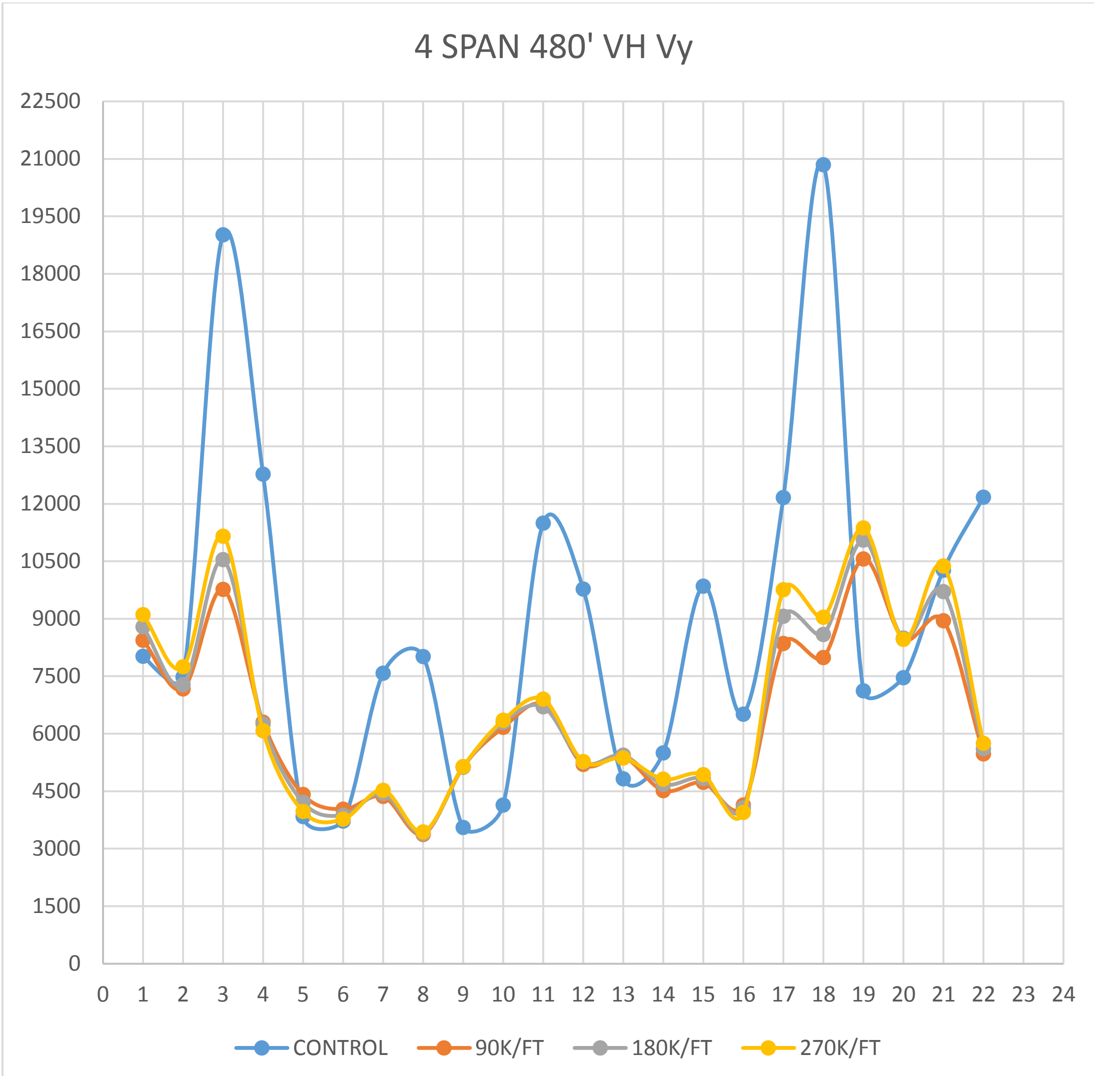


Fig. 4-82 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

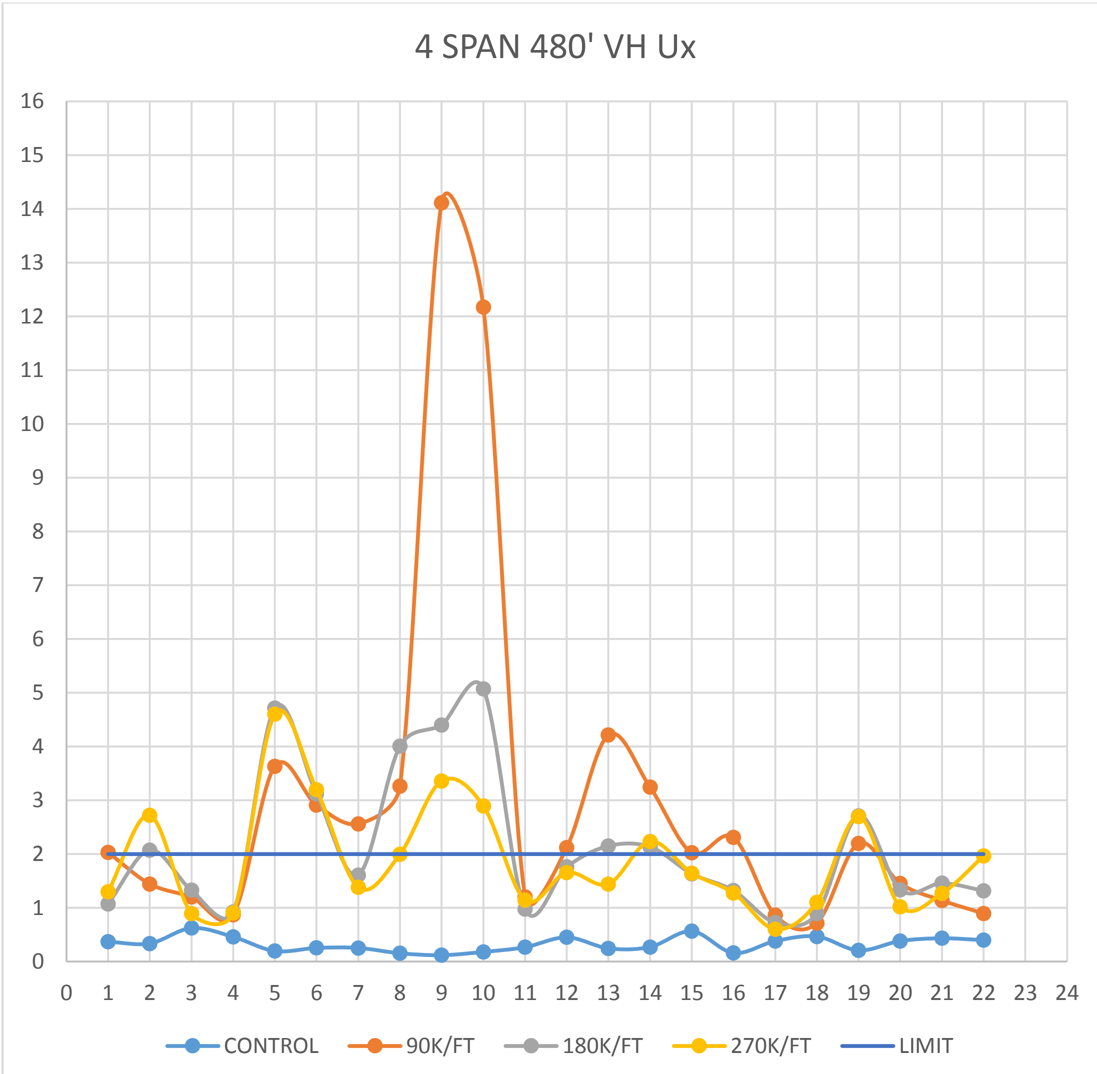


Fig. 4-83 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

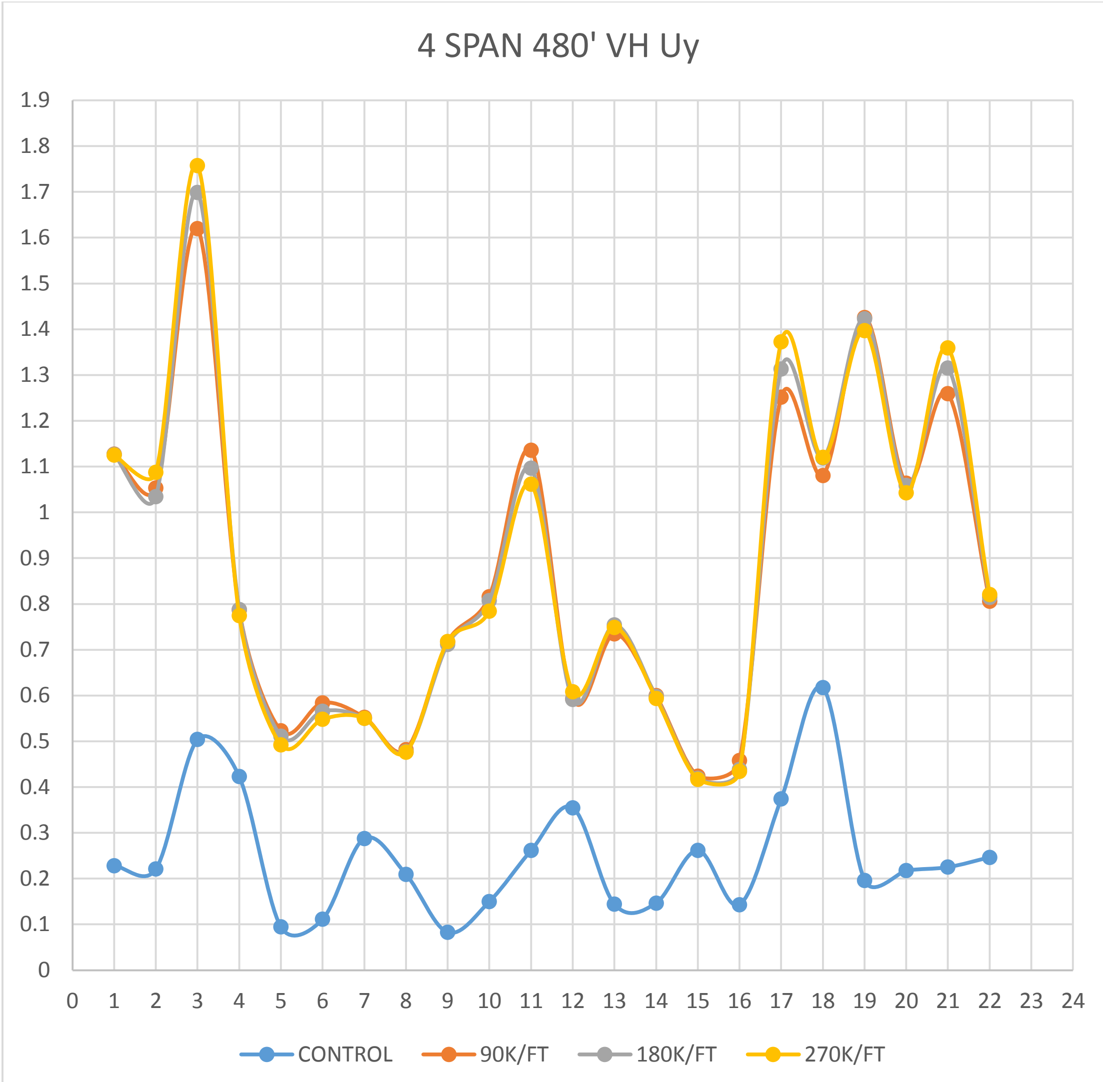


Fig. 4-84 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 23643.39

90 K/Ft = 3265.209

180 K/Ft = 2461.095

270 K/Ft = 3272.602

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

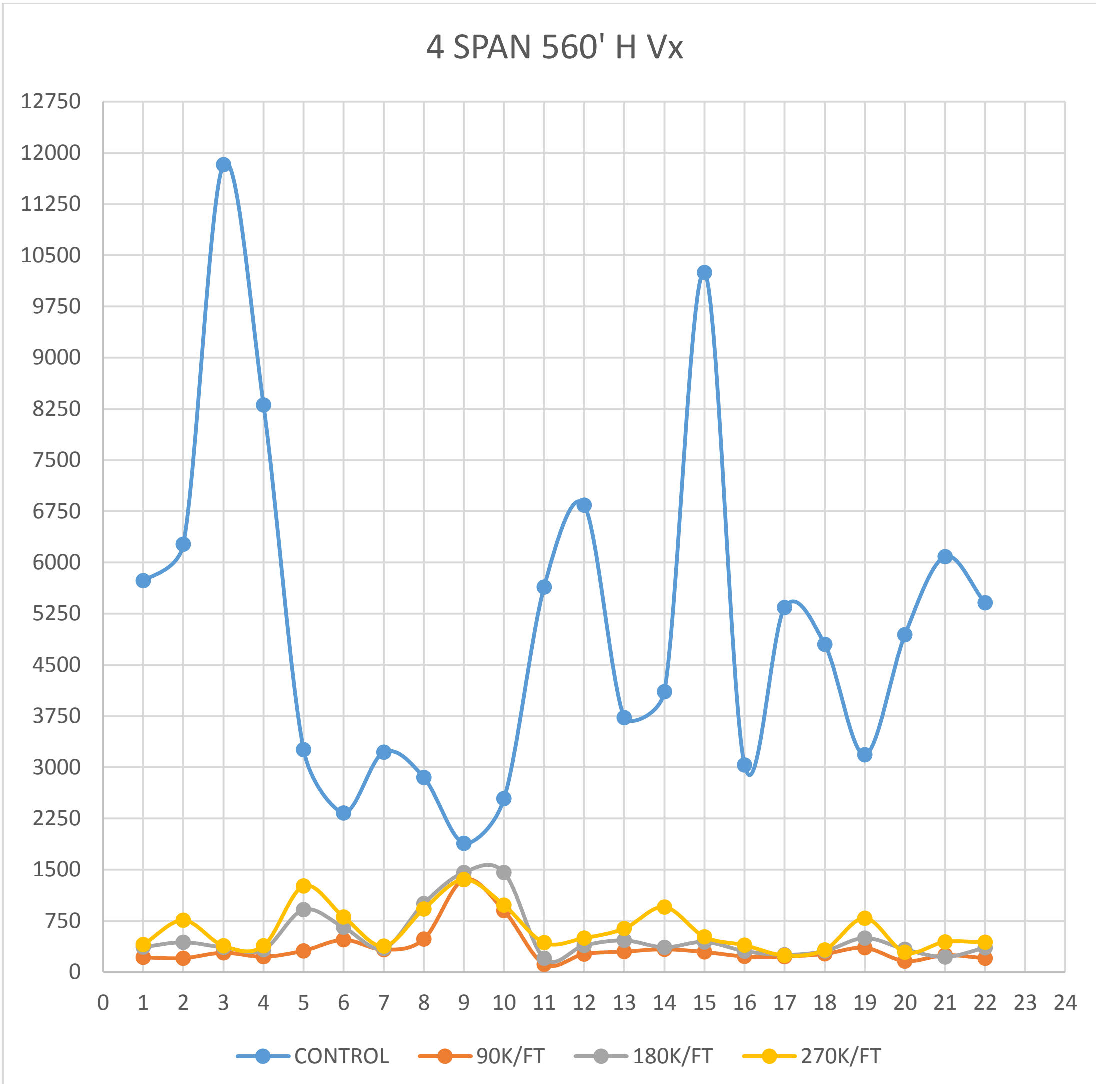


Fig. 4-85 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

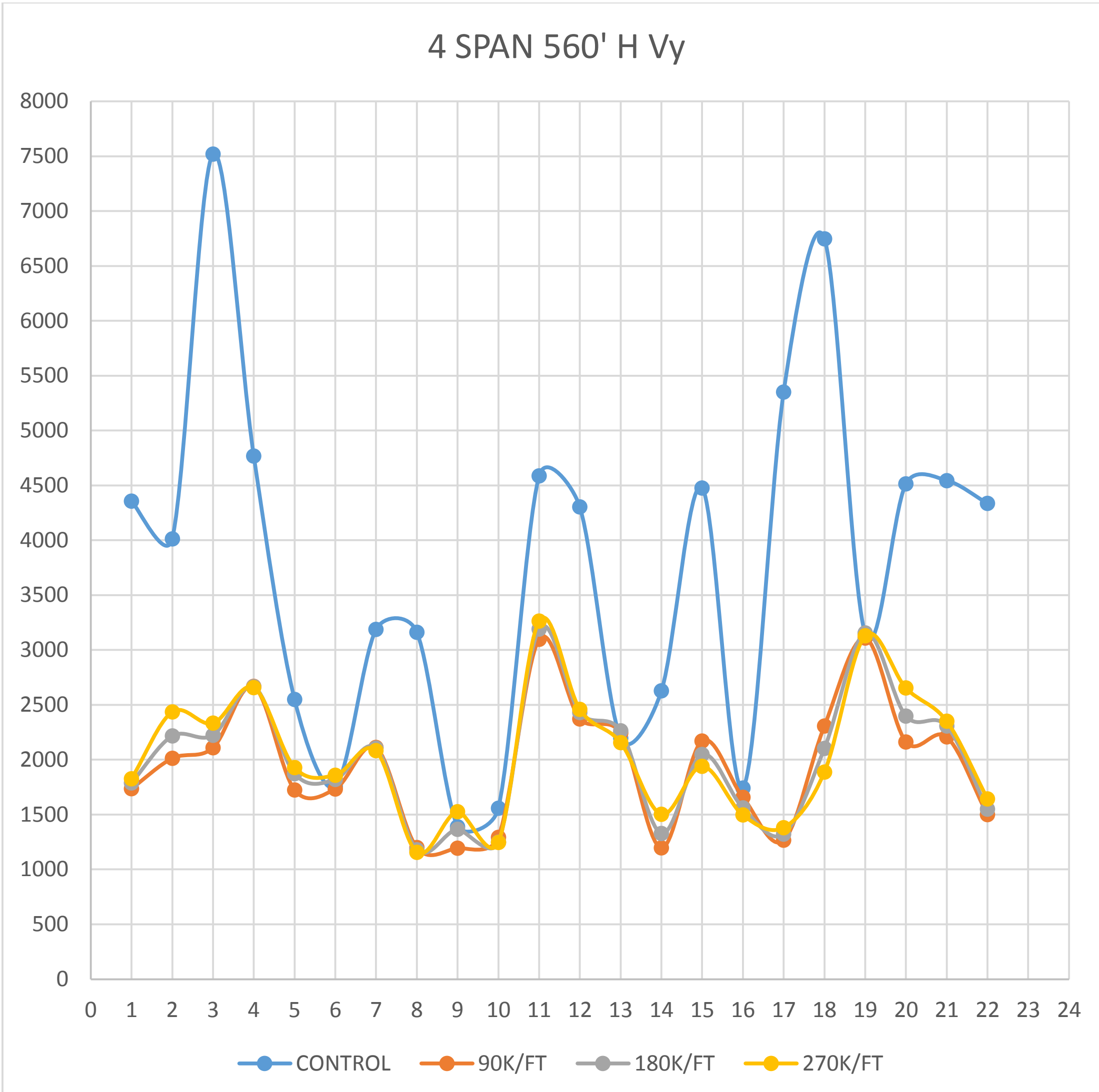


Fig. 4-86 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

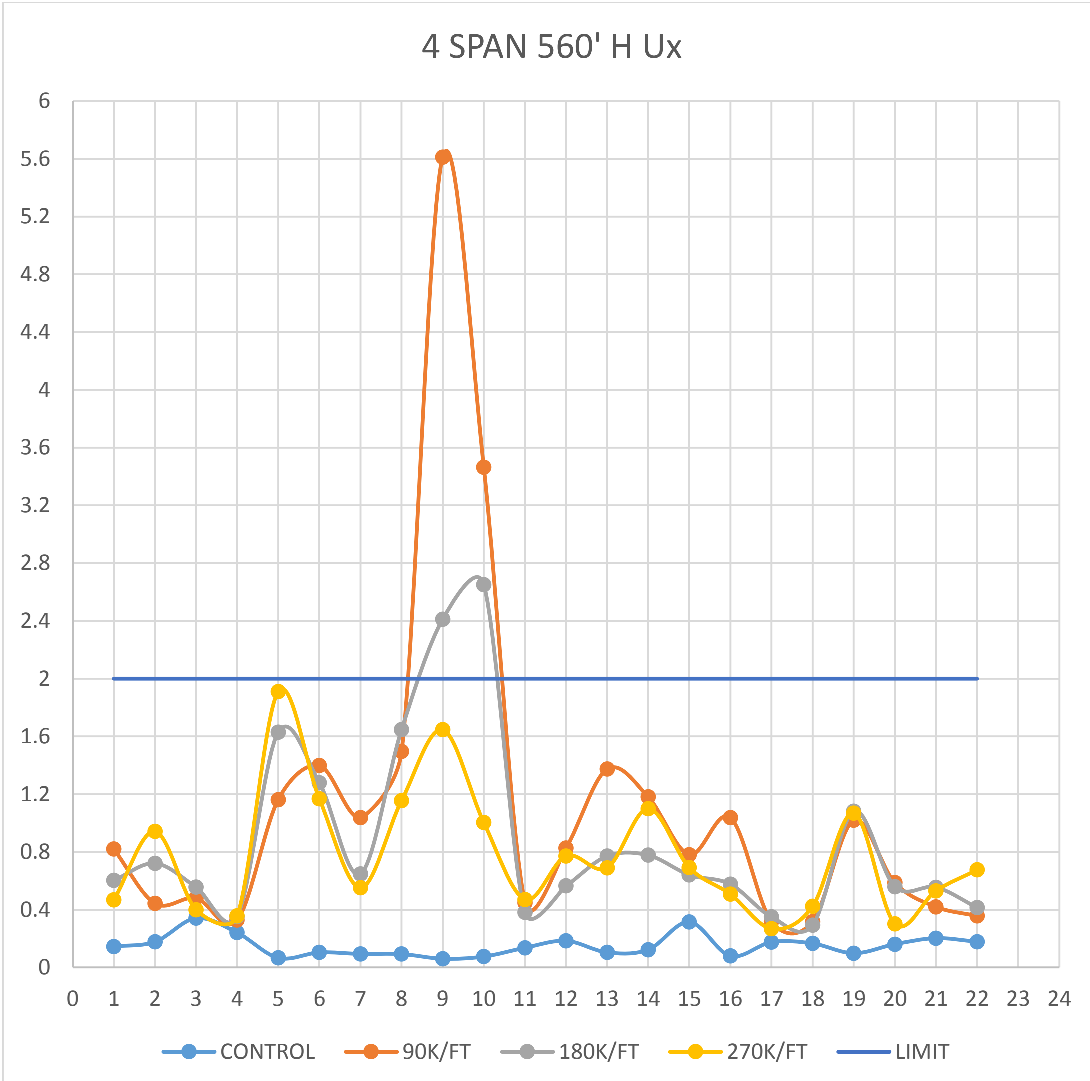


Fig. 4-87 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

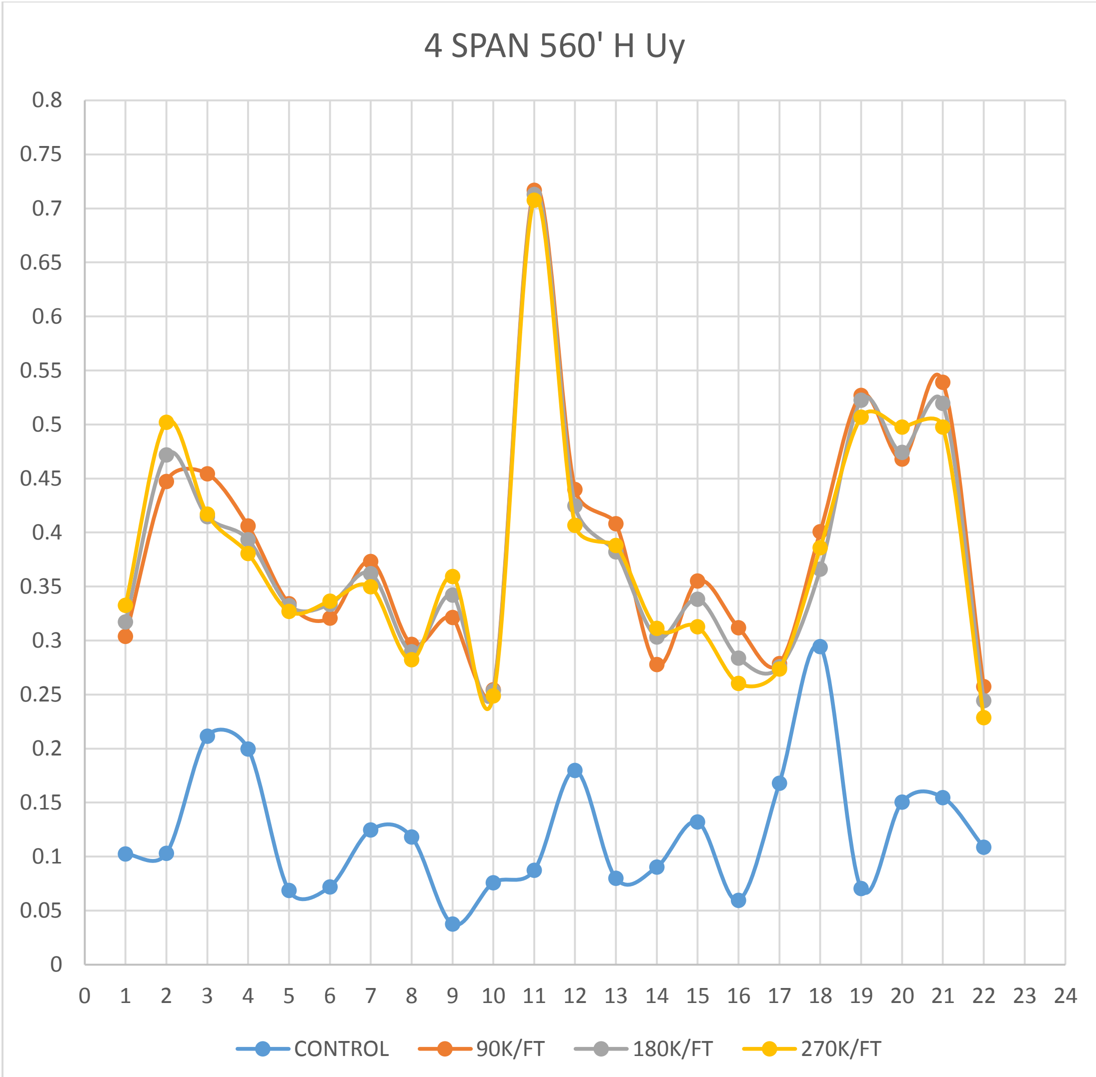


Fig. 4-88 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

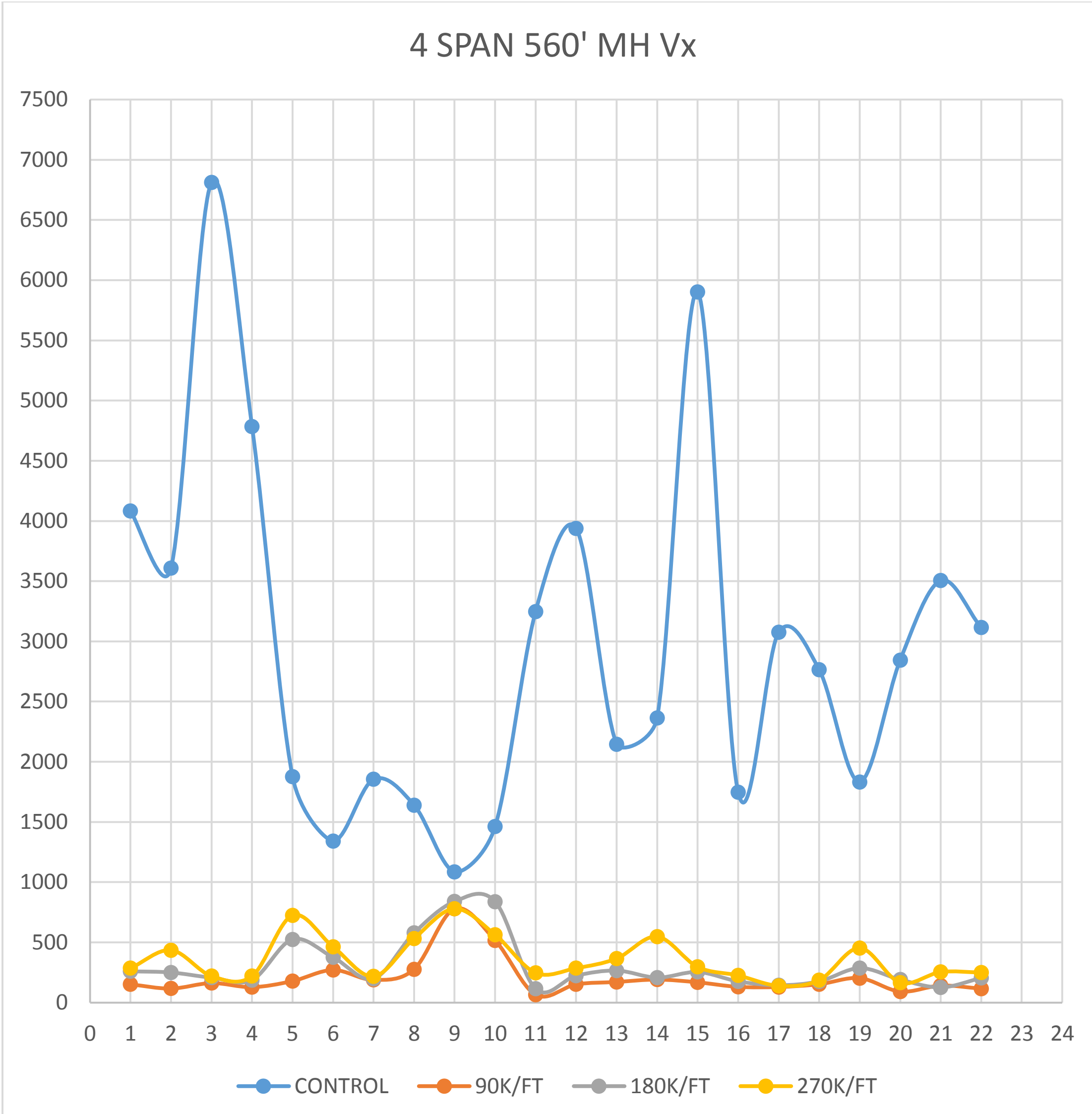


Fig. 4-89 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

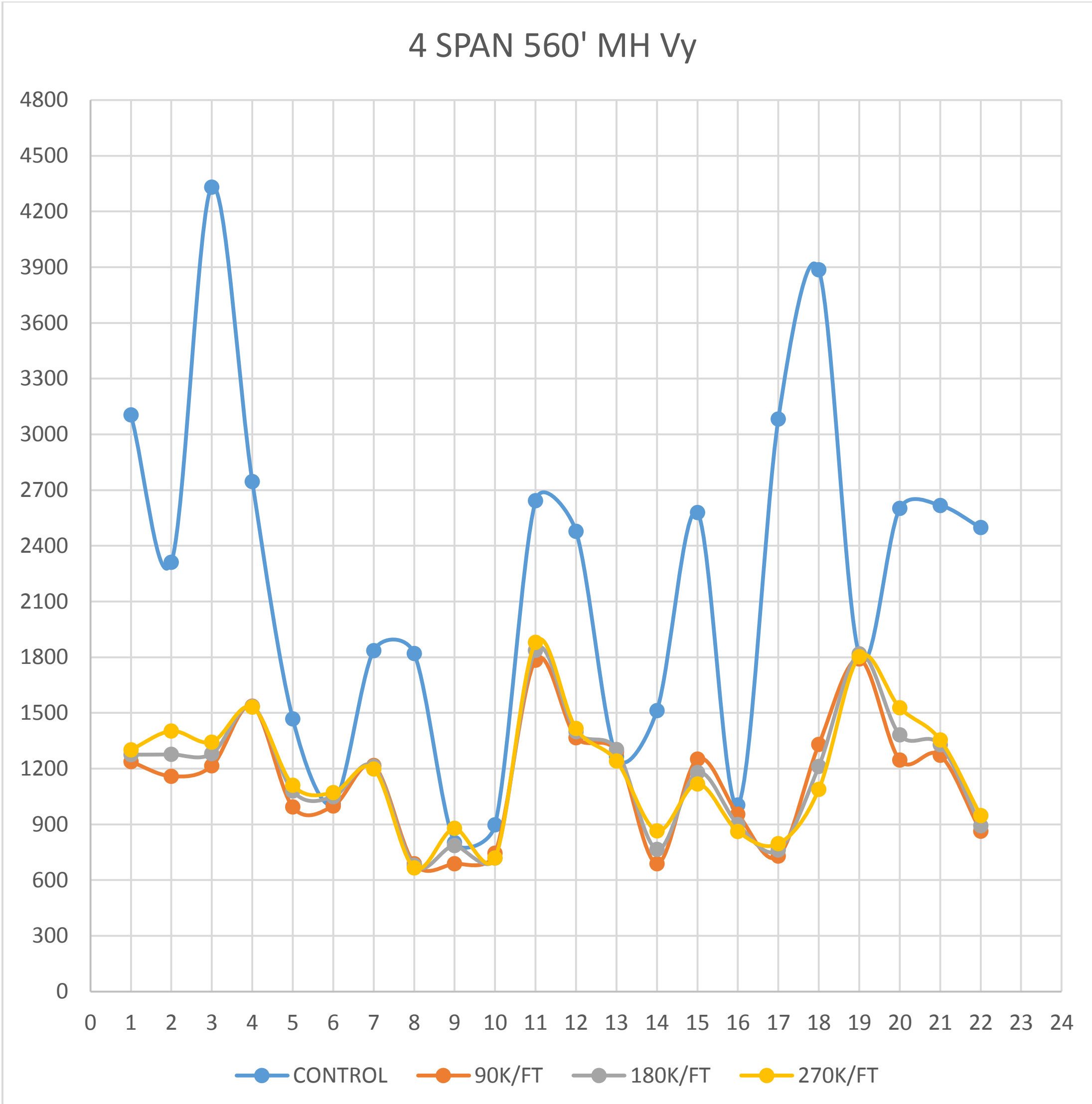


Fig. 4-90 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

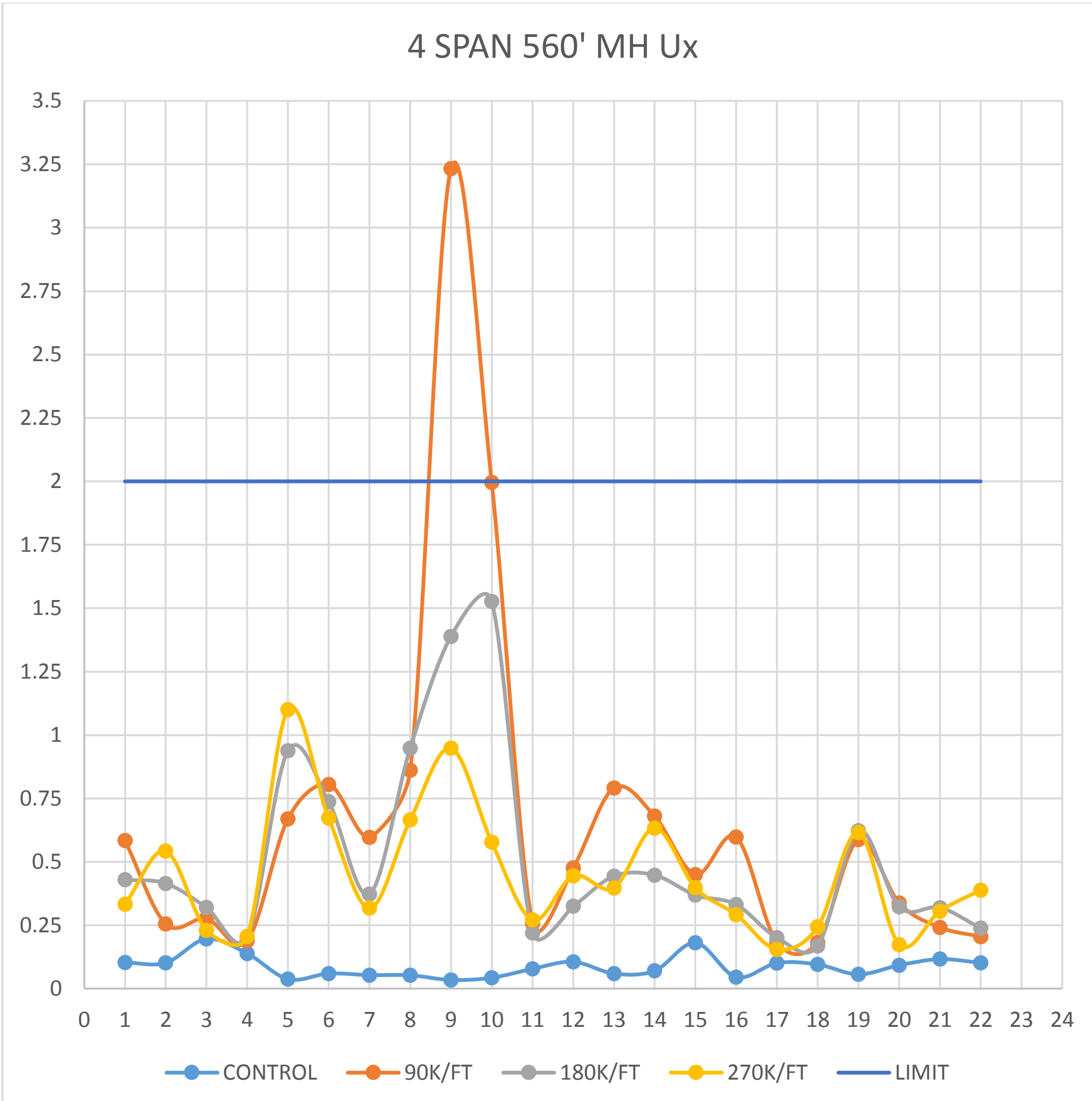


Fig. 4-91 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

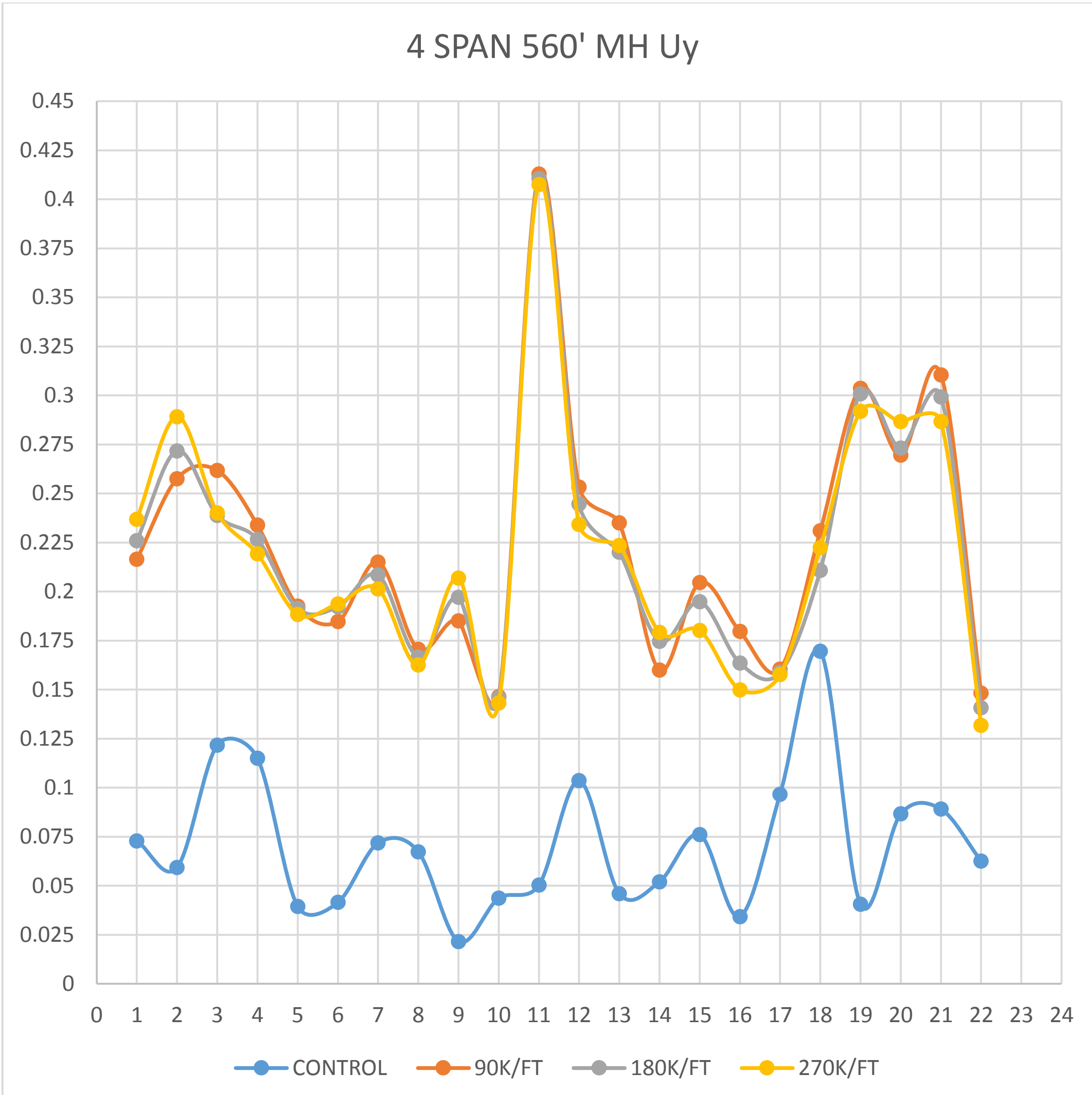


Fig. 4-92 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

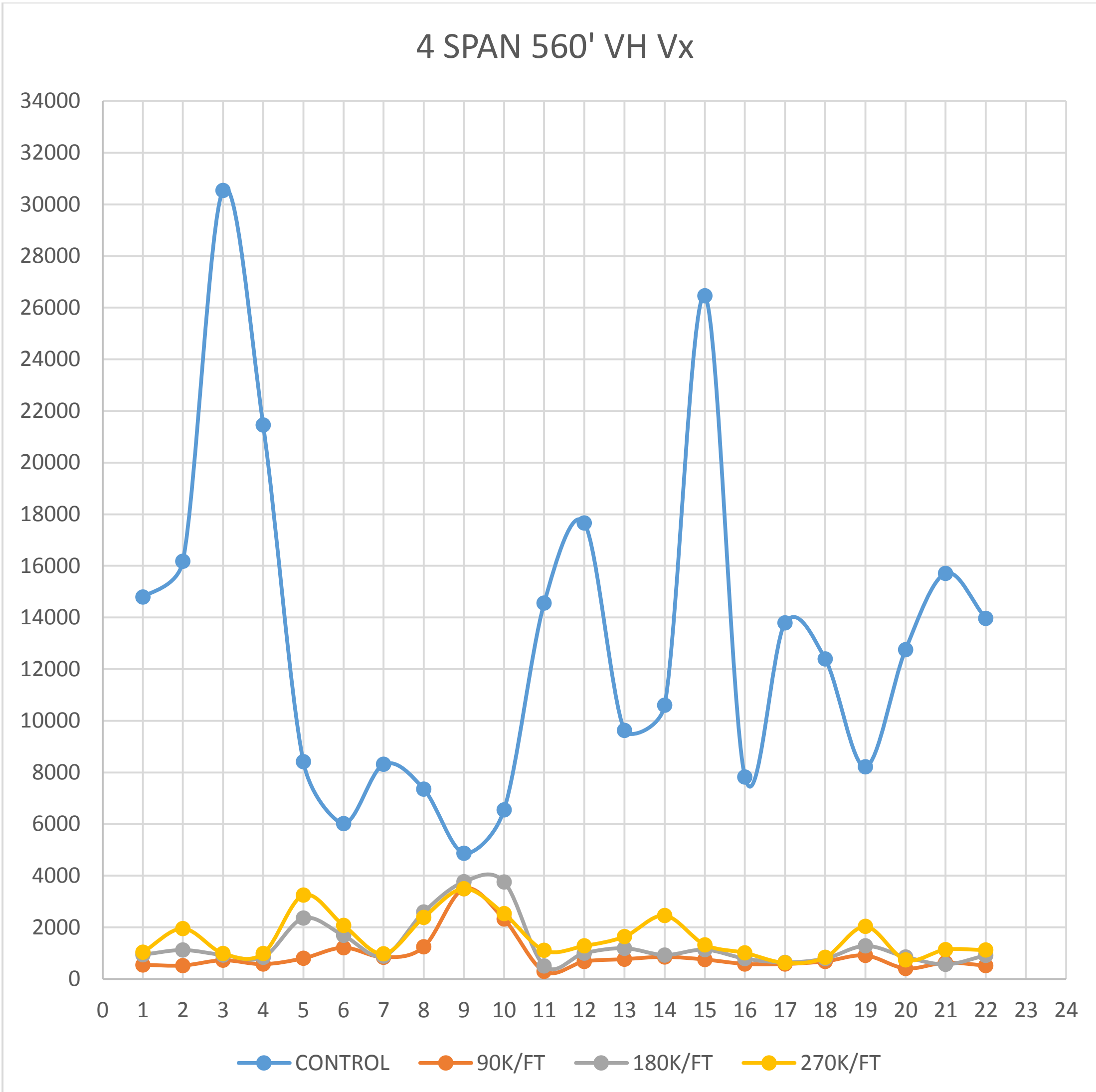


Fig. 4-93 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

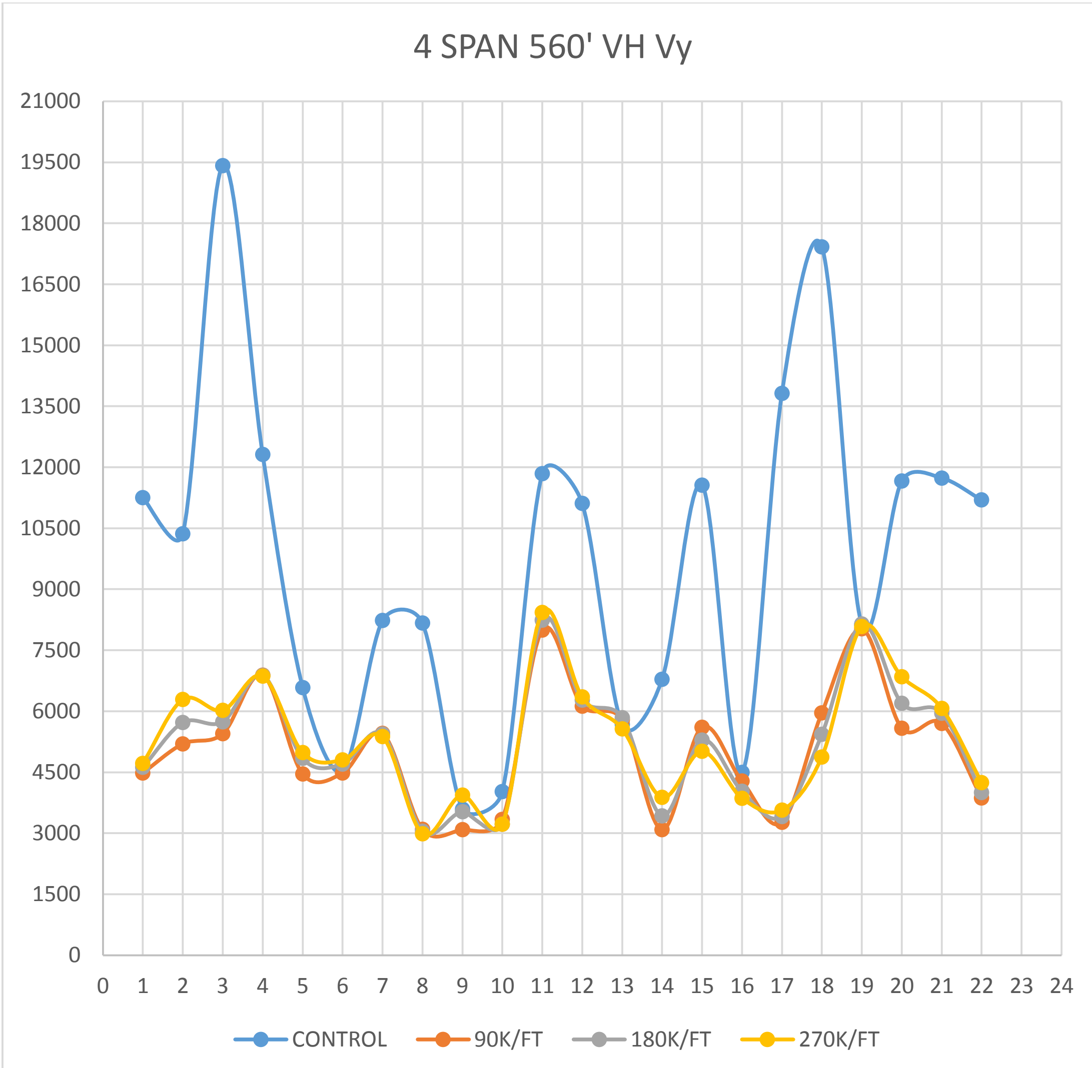


Fig. 4-94 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

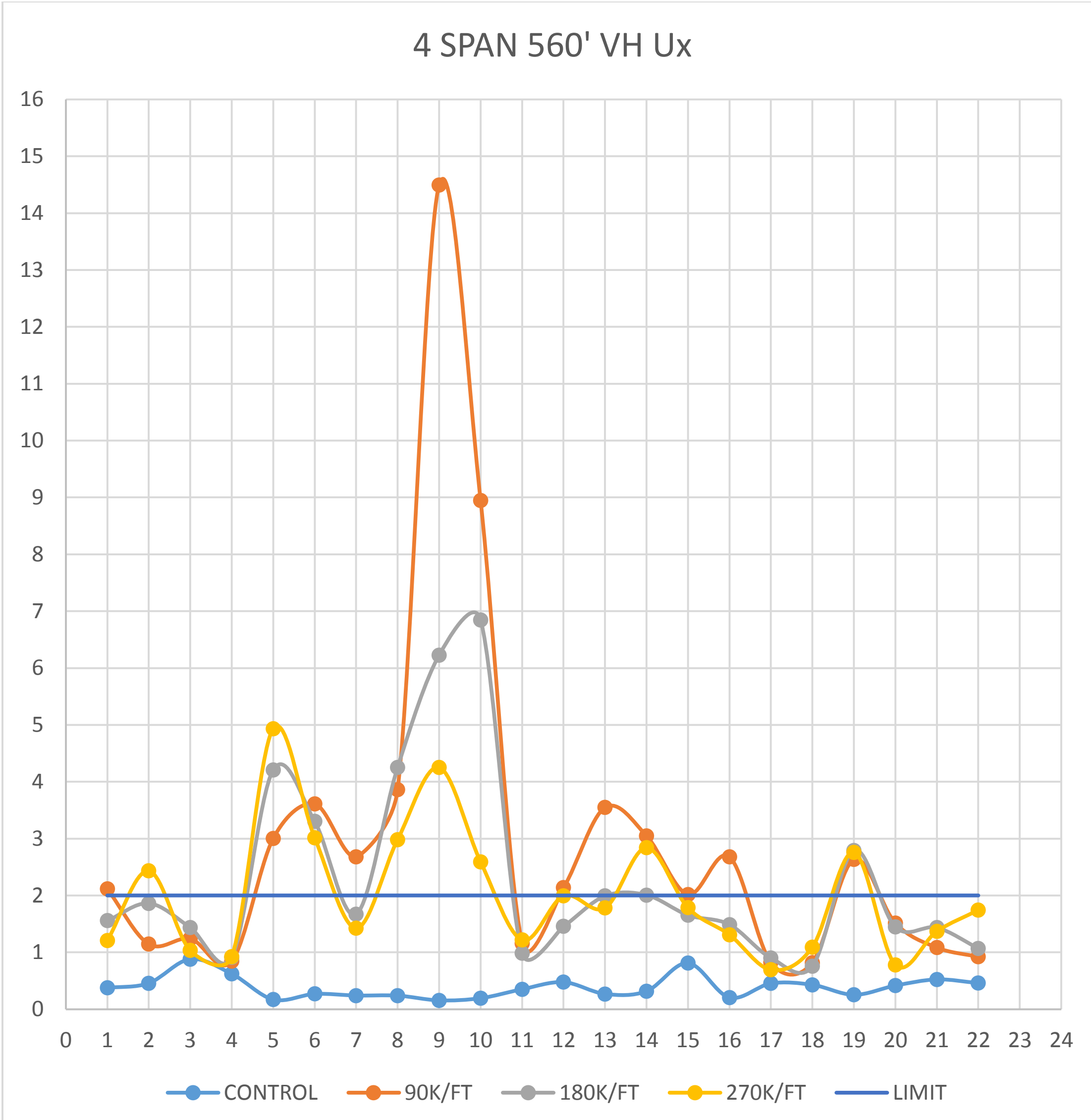


Fig. 4-95 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

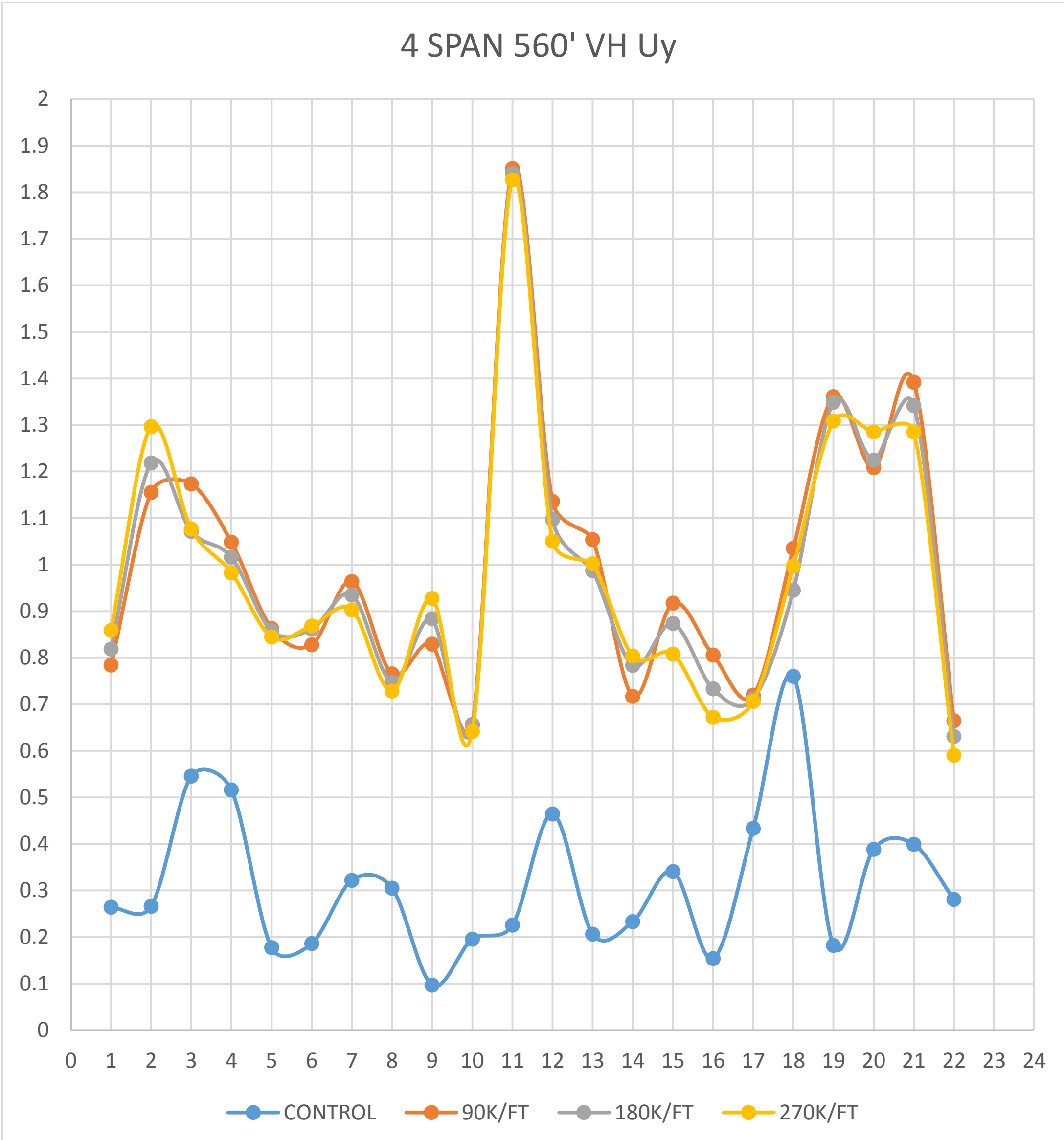


Fig. 4-96 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 30542.09

90 K/Ft = 3491.377

180 K/Ft = 3761.436

270 K/Ft = 3492.54

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

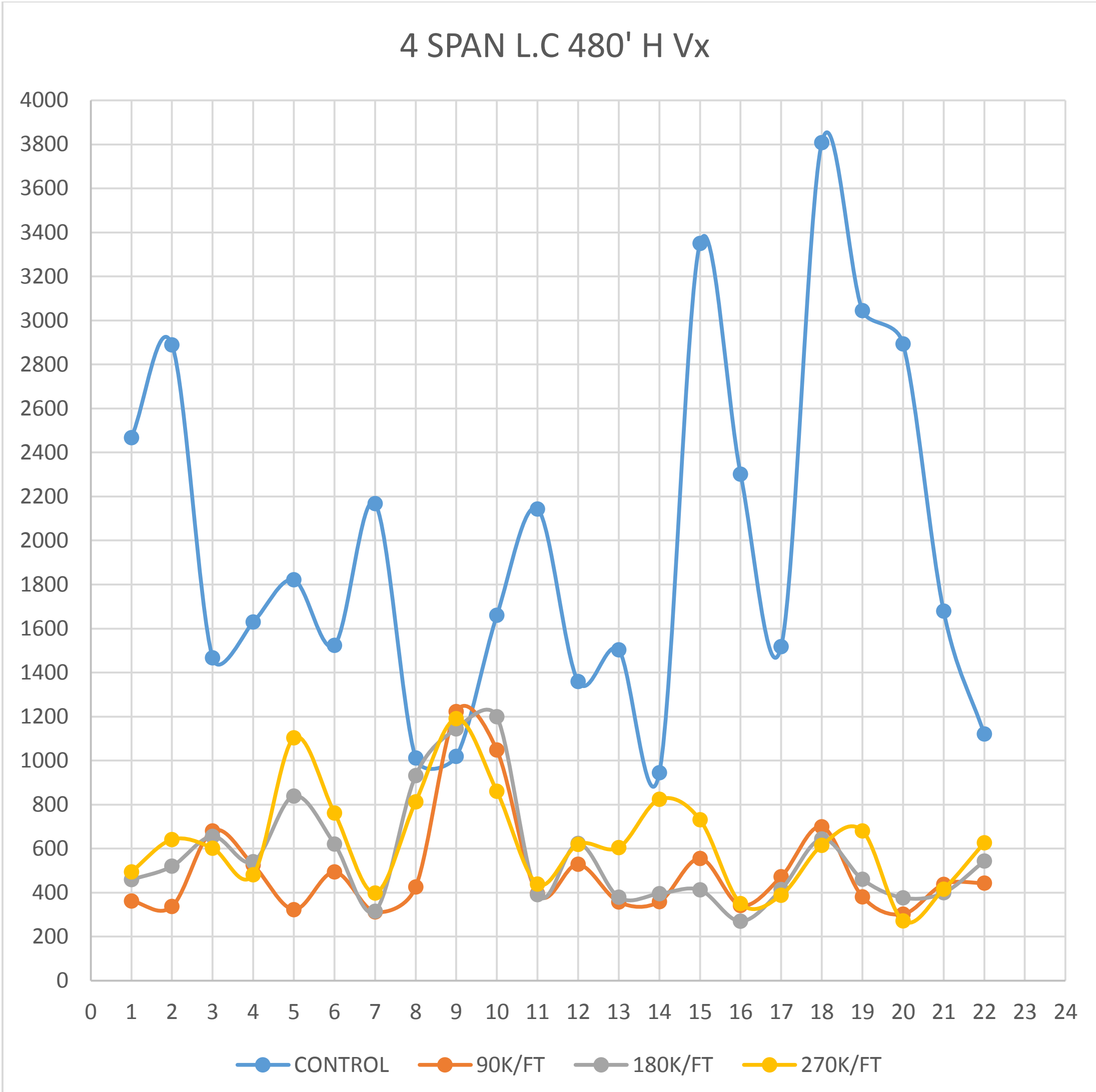


Fig. 4-97 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

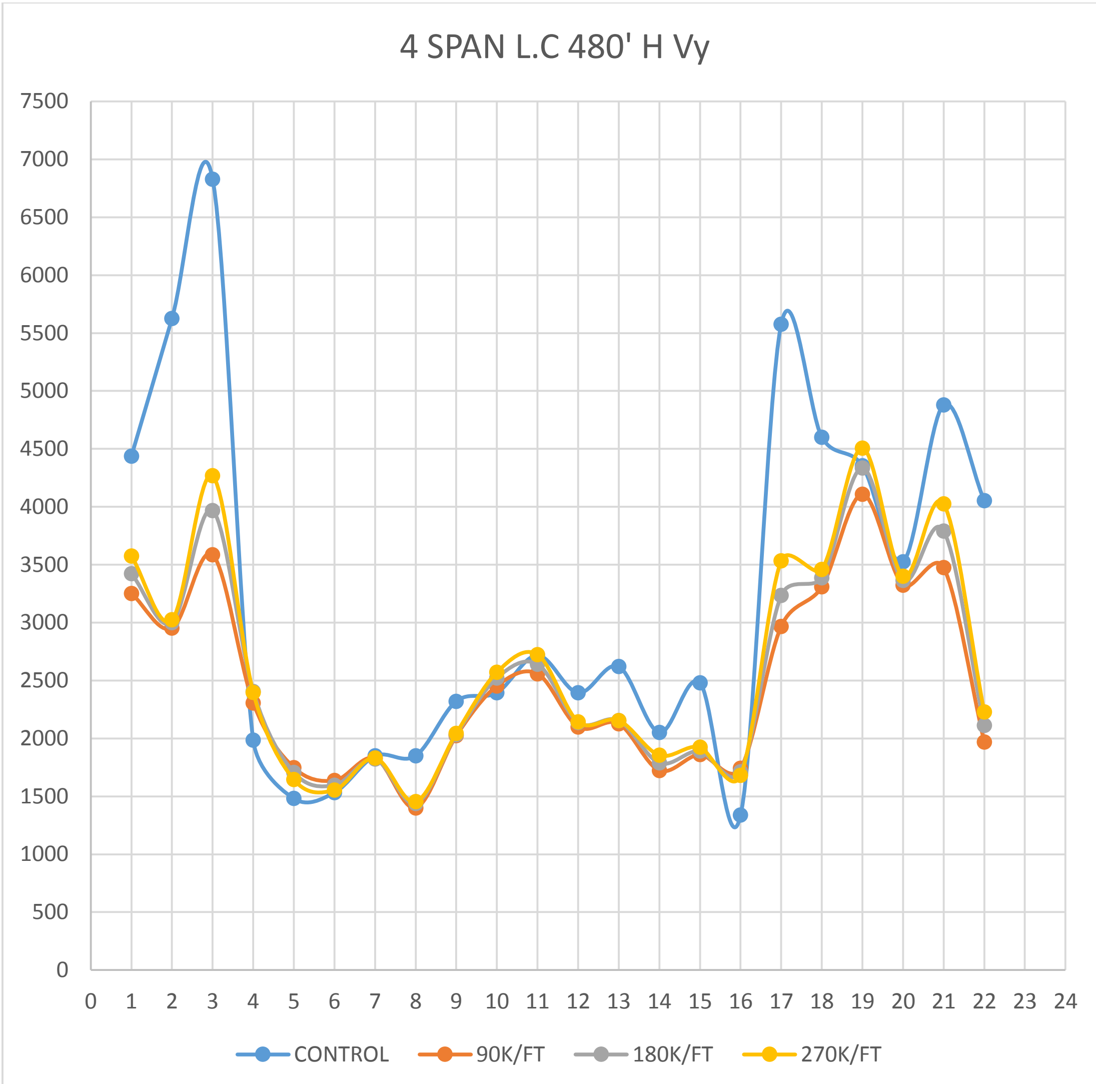


Fig. 4-98 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

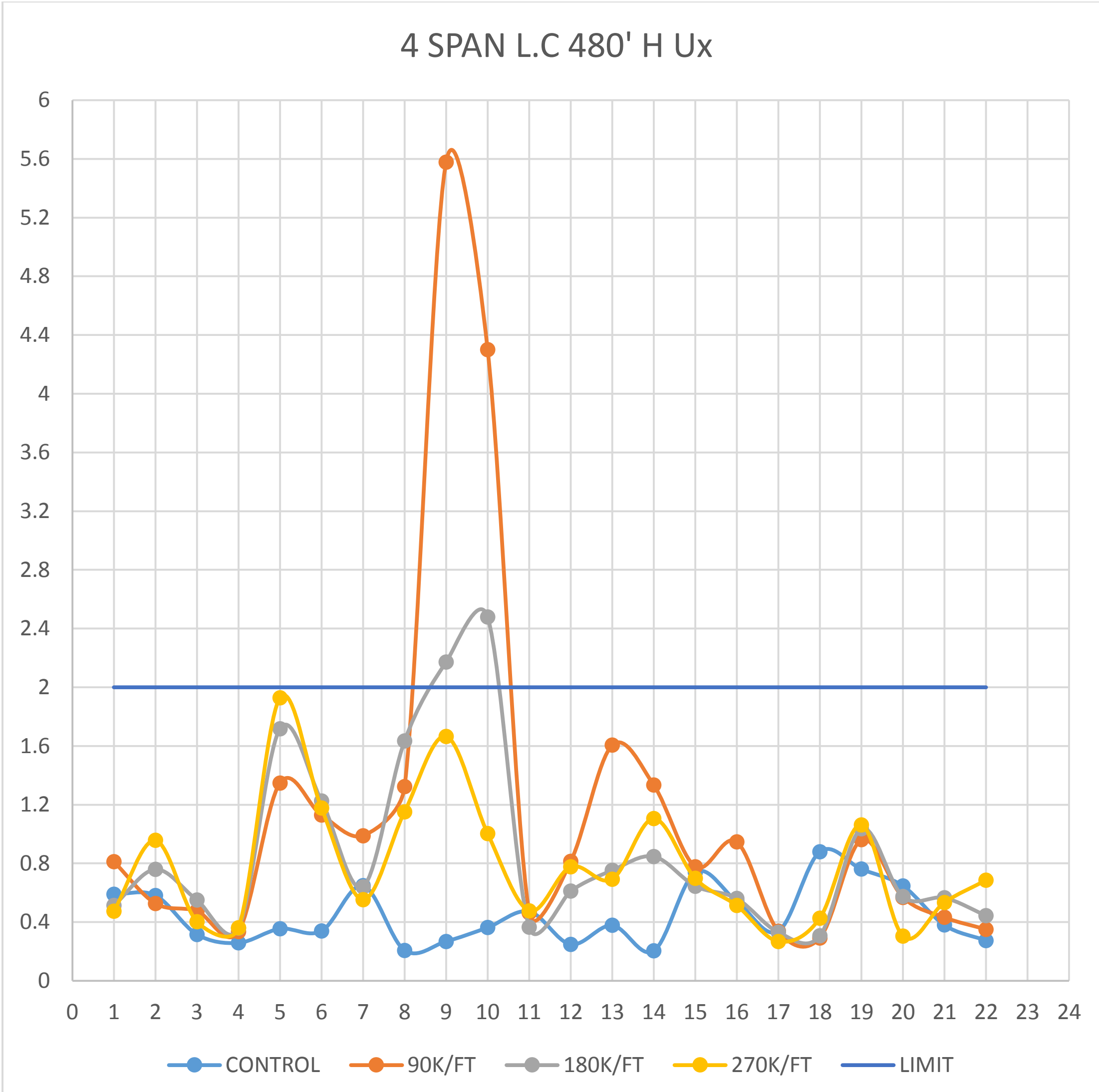


Fig. 4-99 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

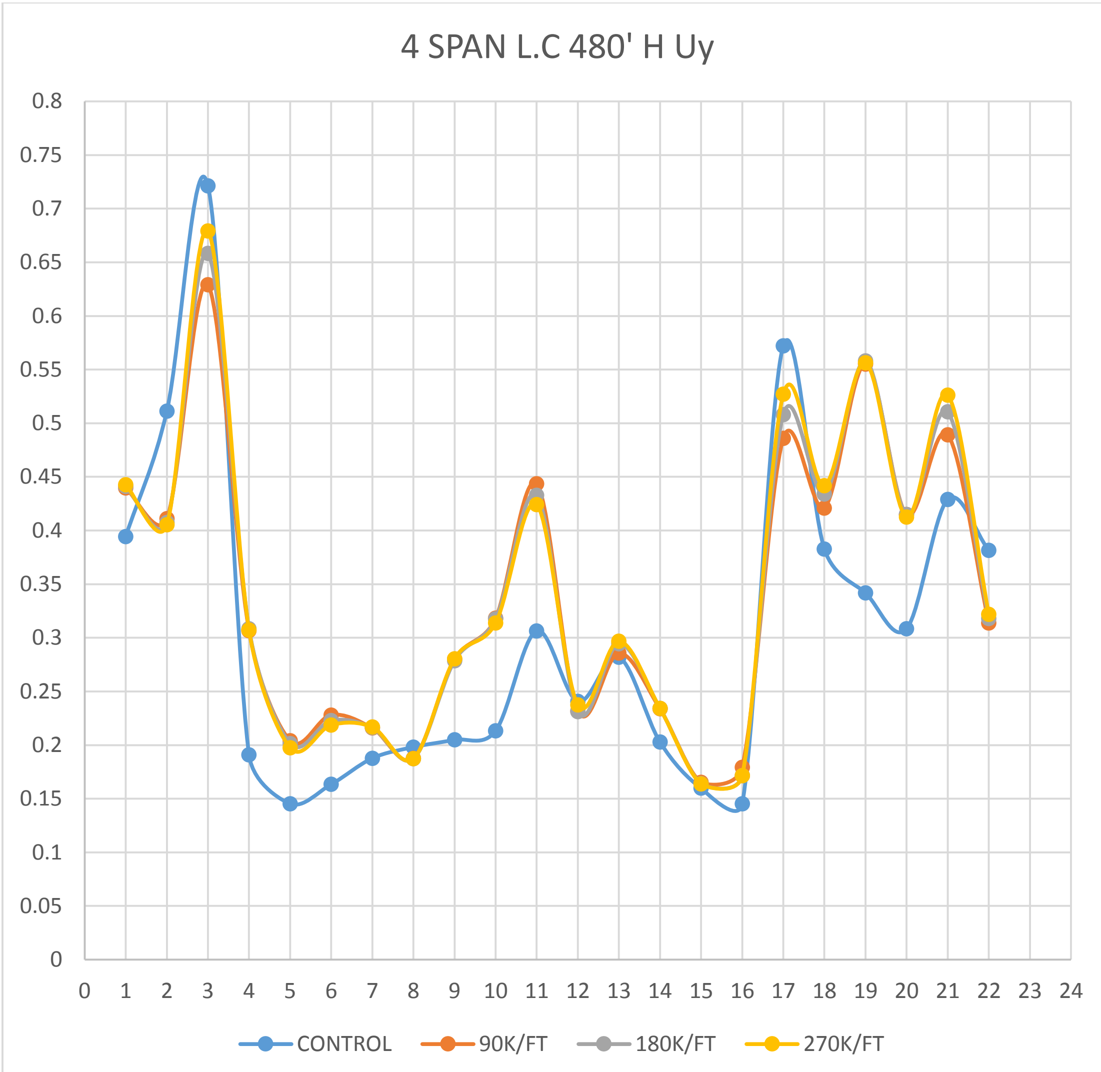


Fig. 4-100 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

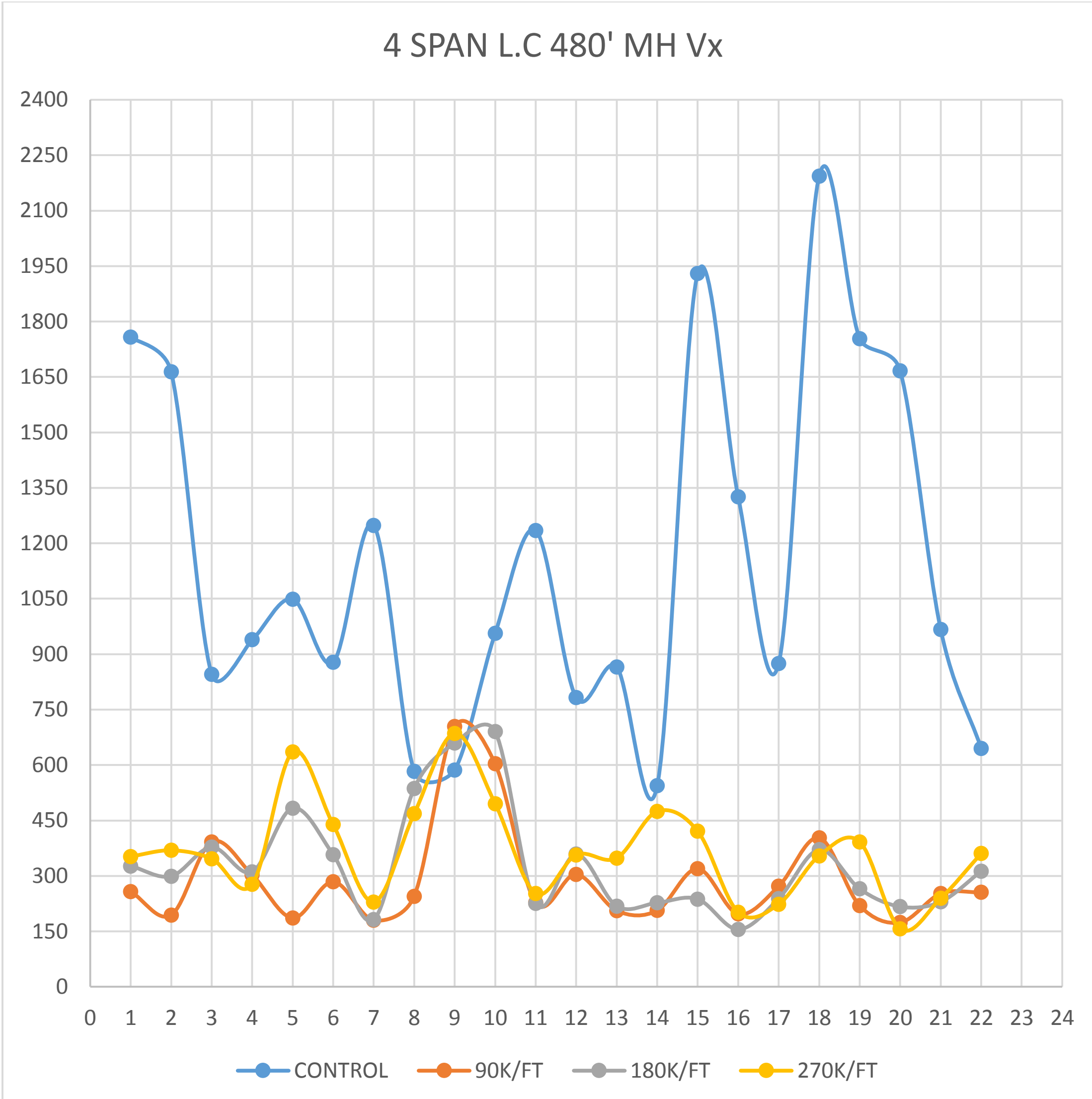


Fig. 4-101 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

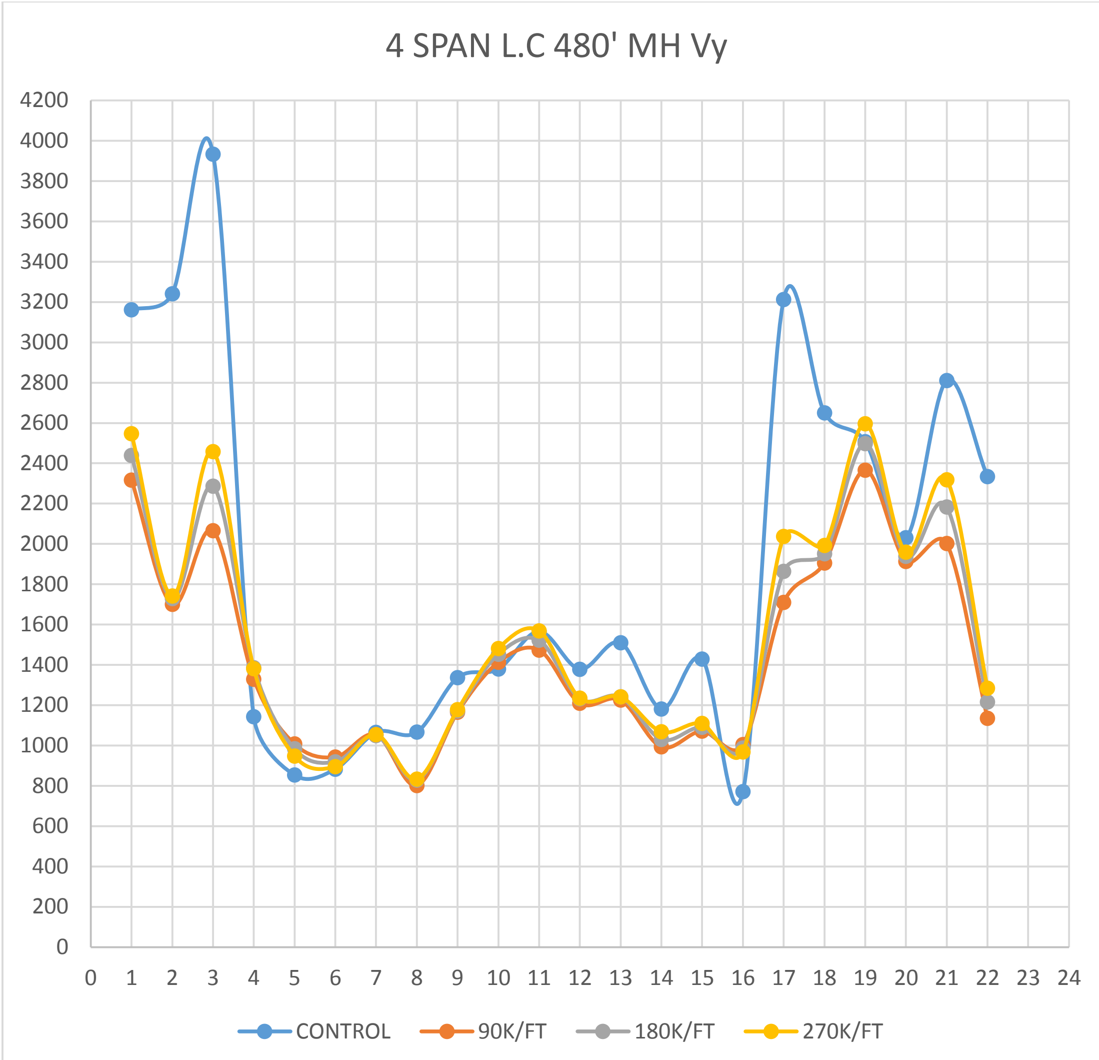


Fig. 4-102 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

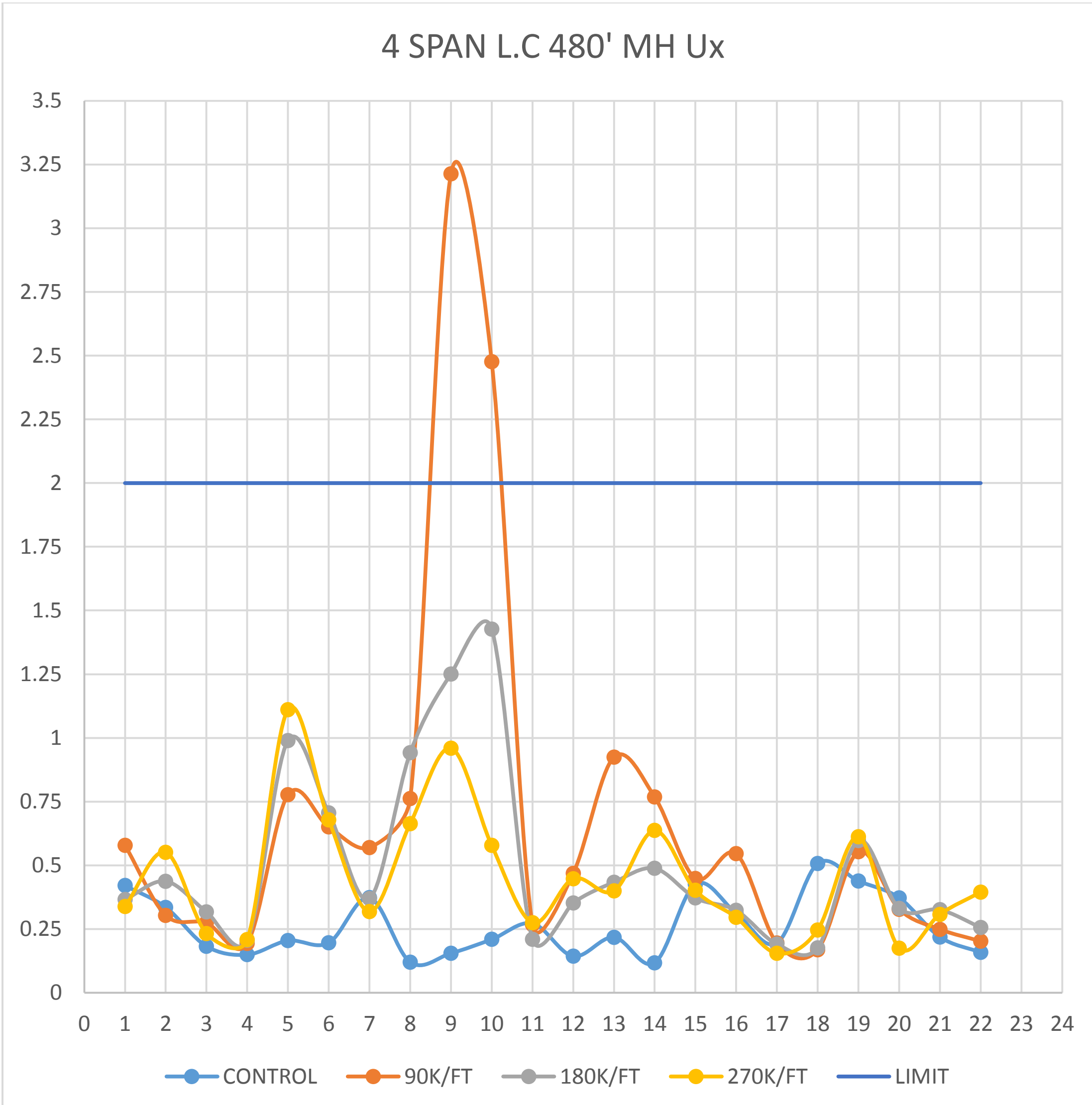


Fig. 4-103 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

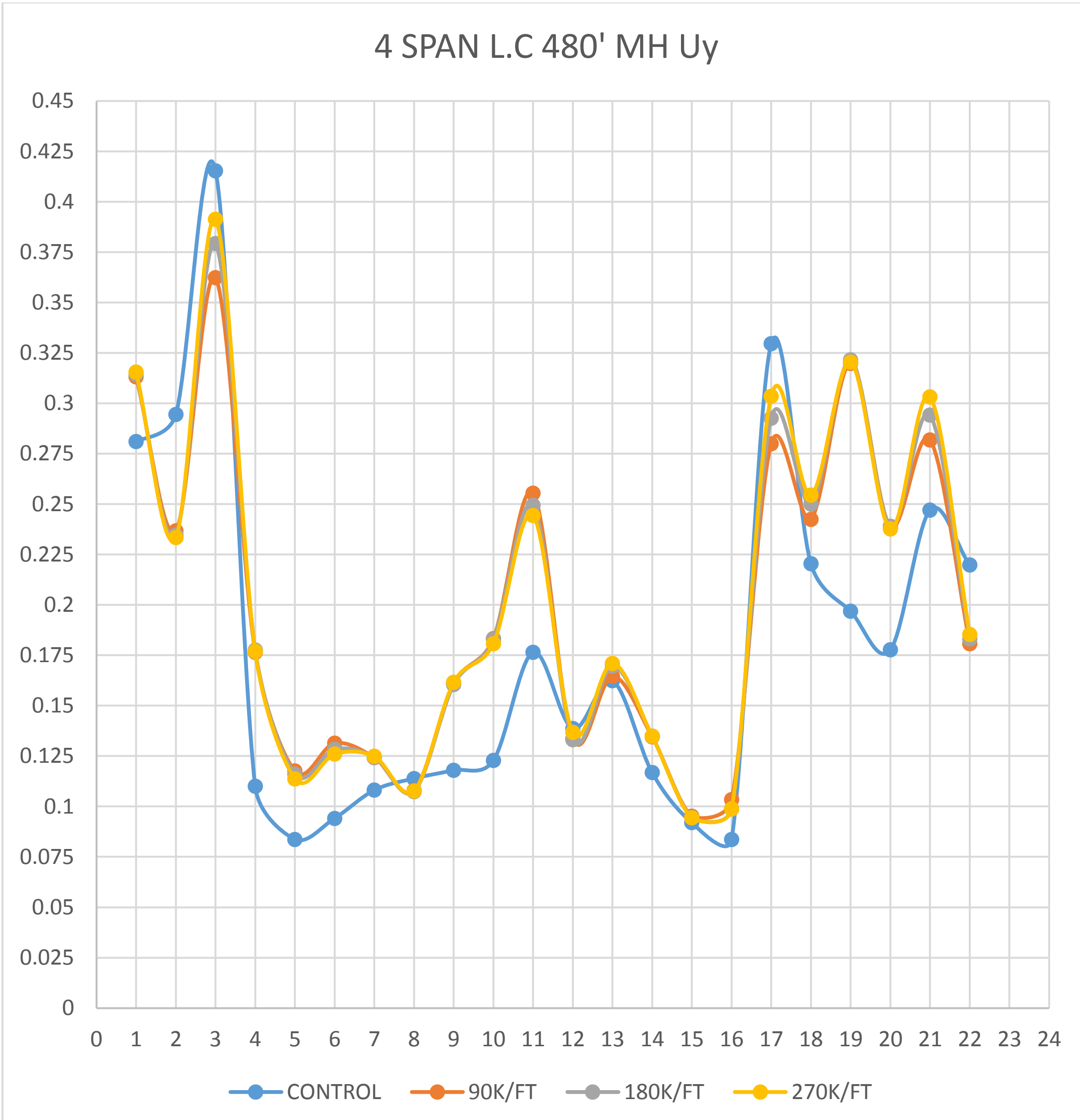


Fig. 4-104 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

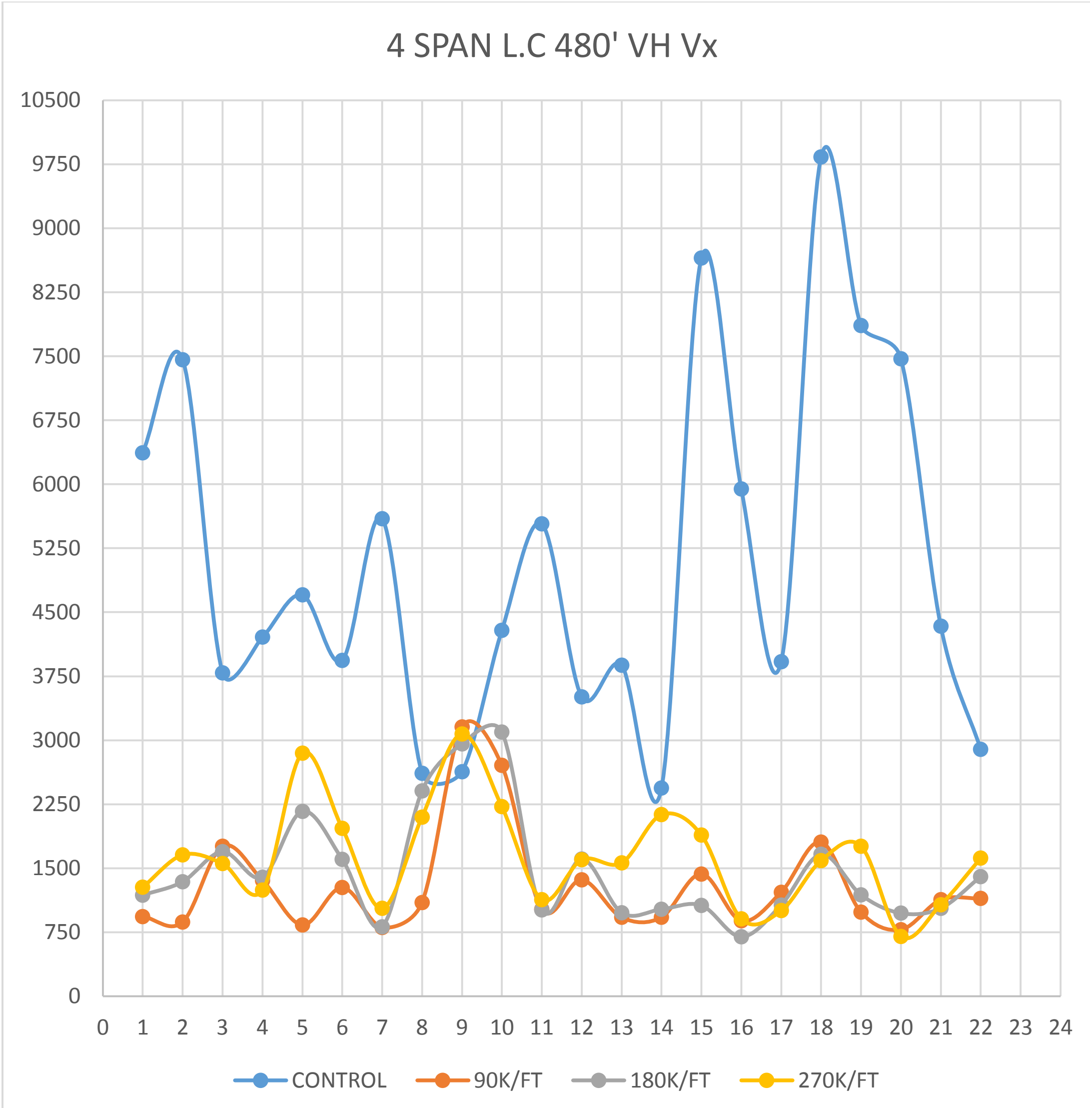


Fig. 4-105 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

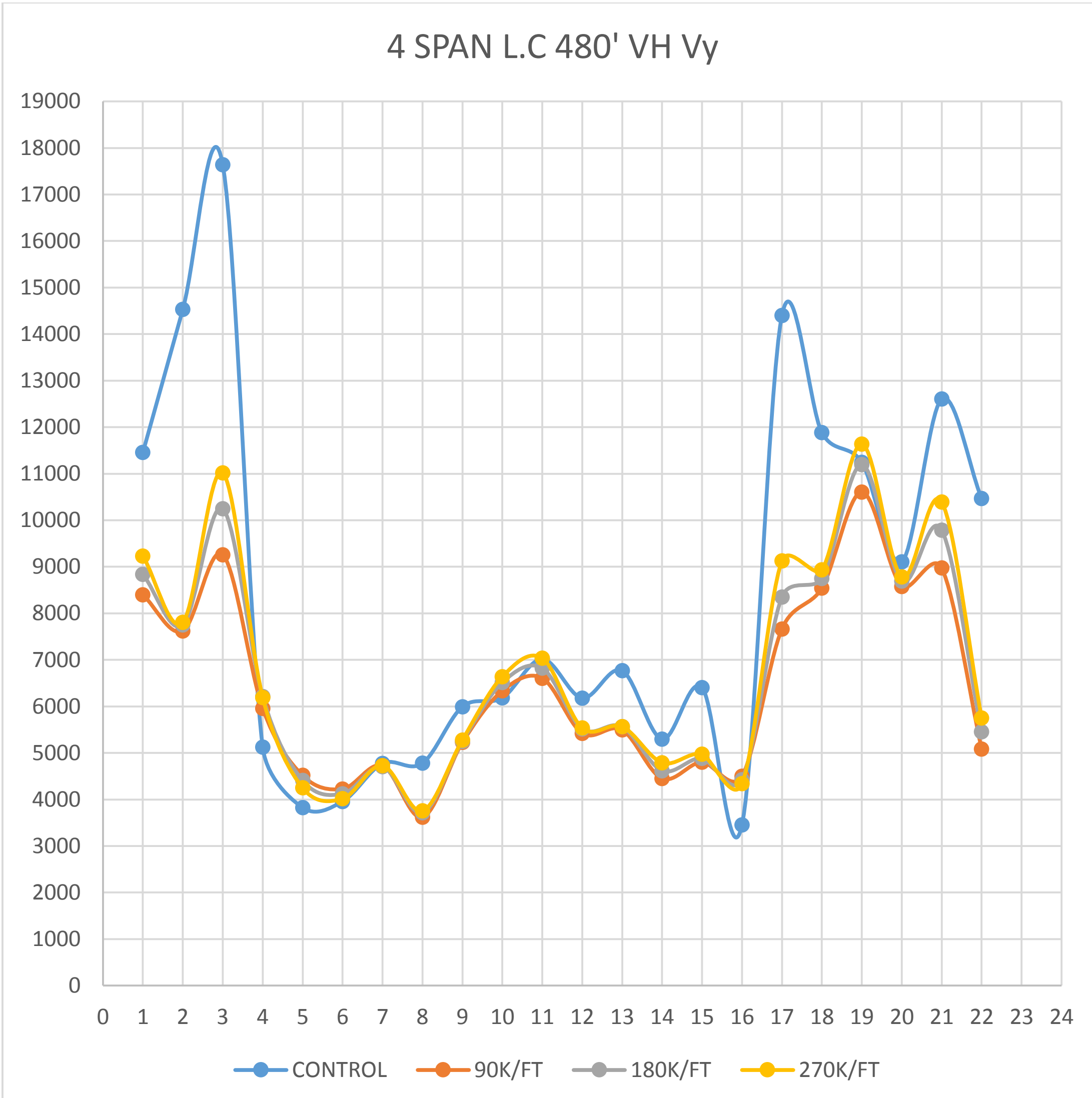


Fig. 4-106 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

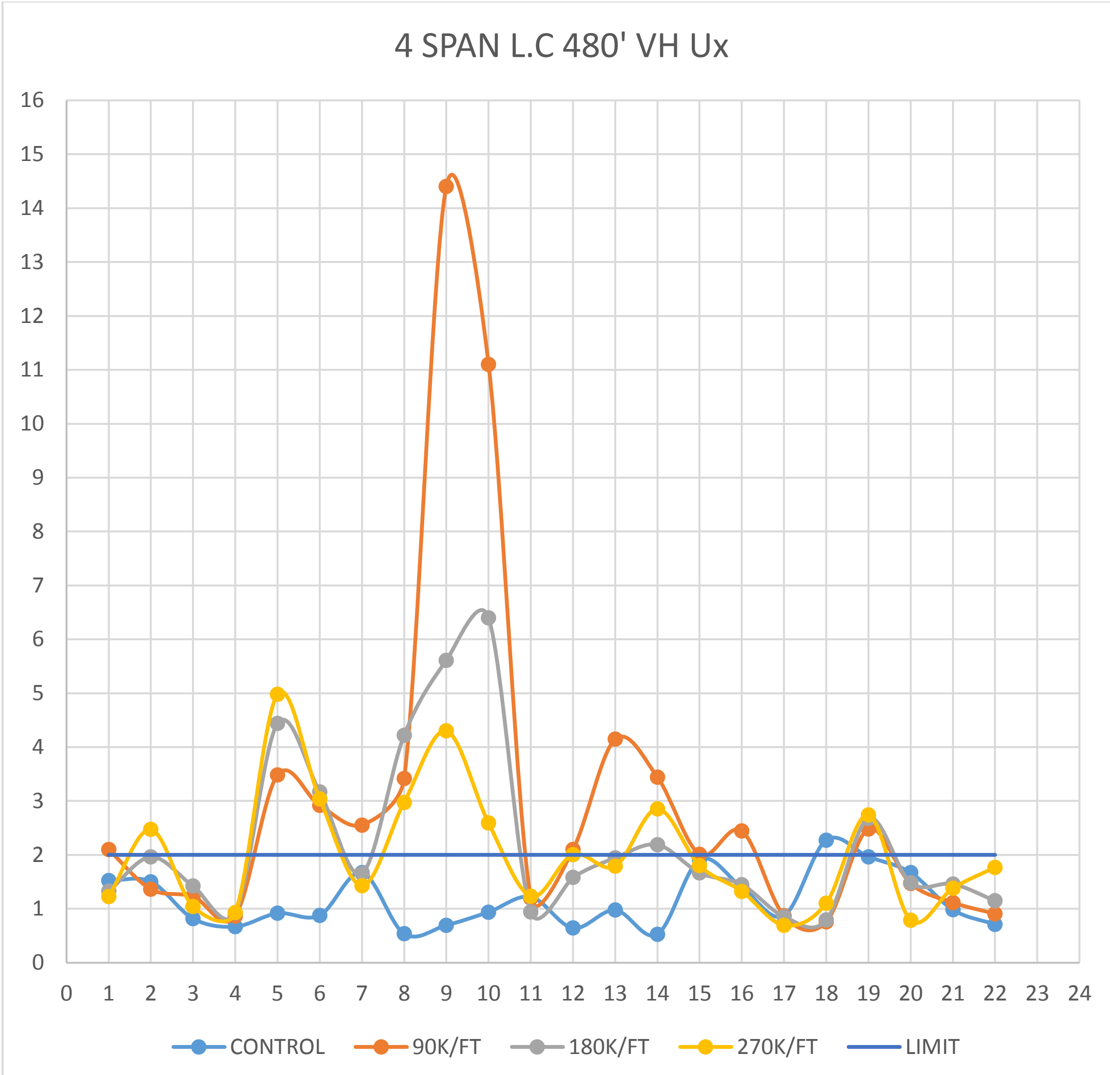


Fig. 4-107 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

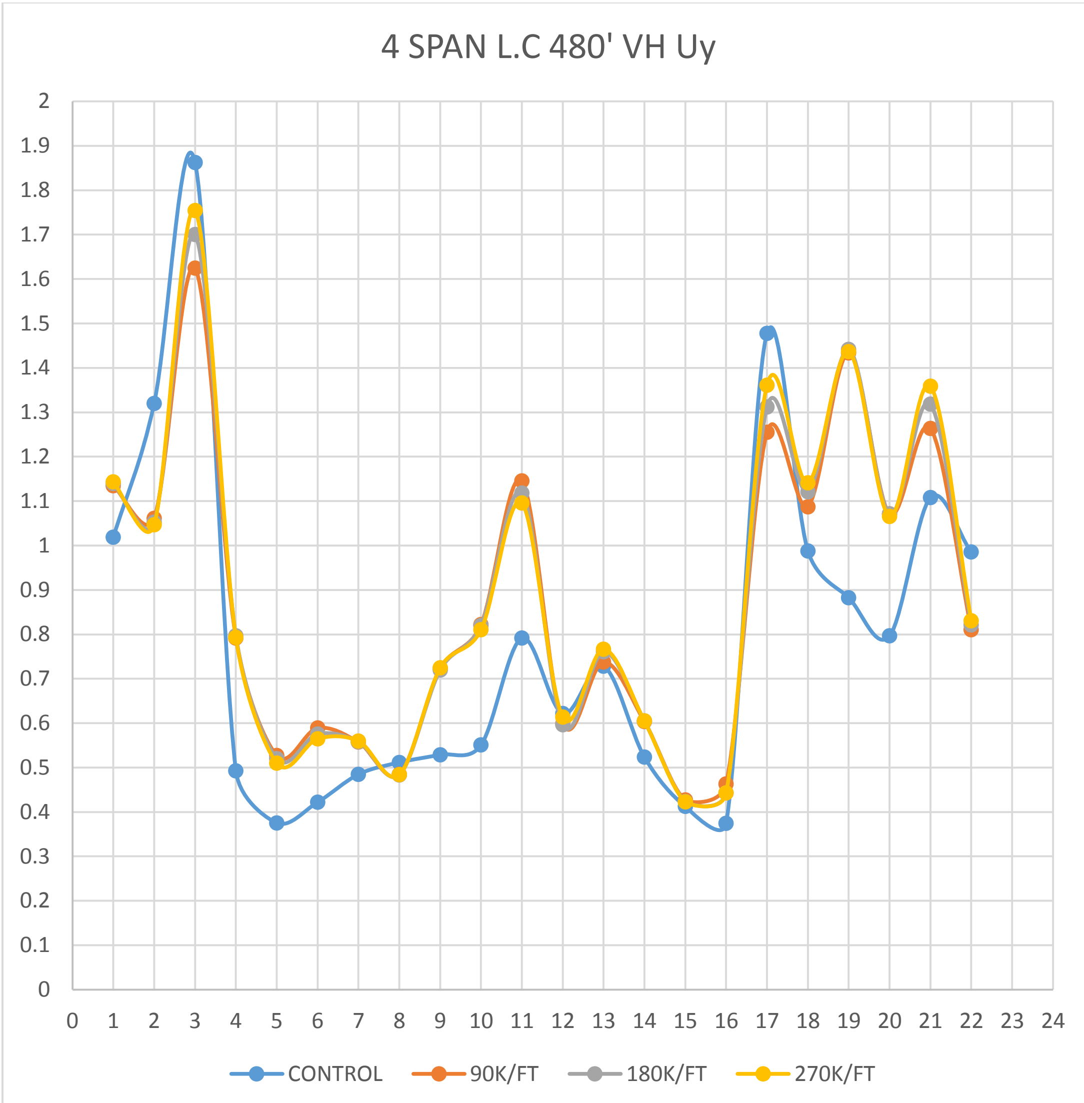


Fig. 4-108 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

The maximum longitudinal base shear values recorded for this case are:

Control = 9834.969

90 K/Ft = 3155.885

180 K/Ft = 3096.044

270 K/Ft = 3073.221

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

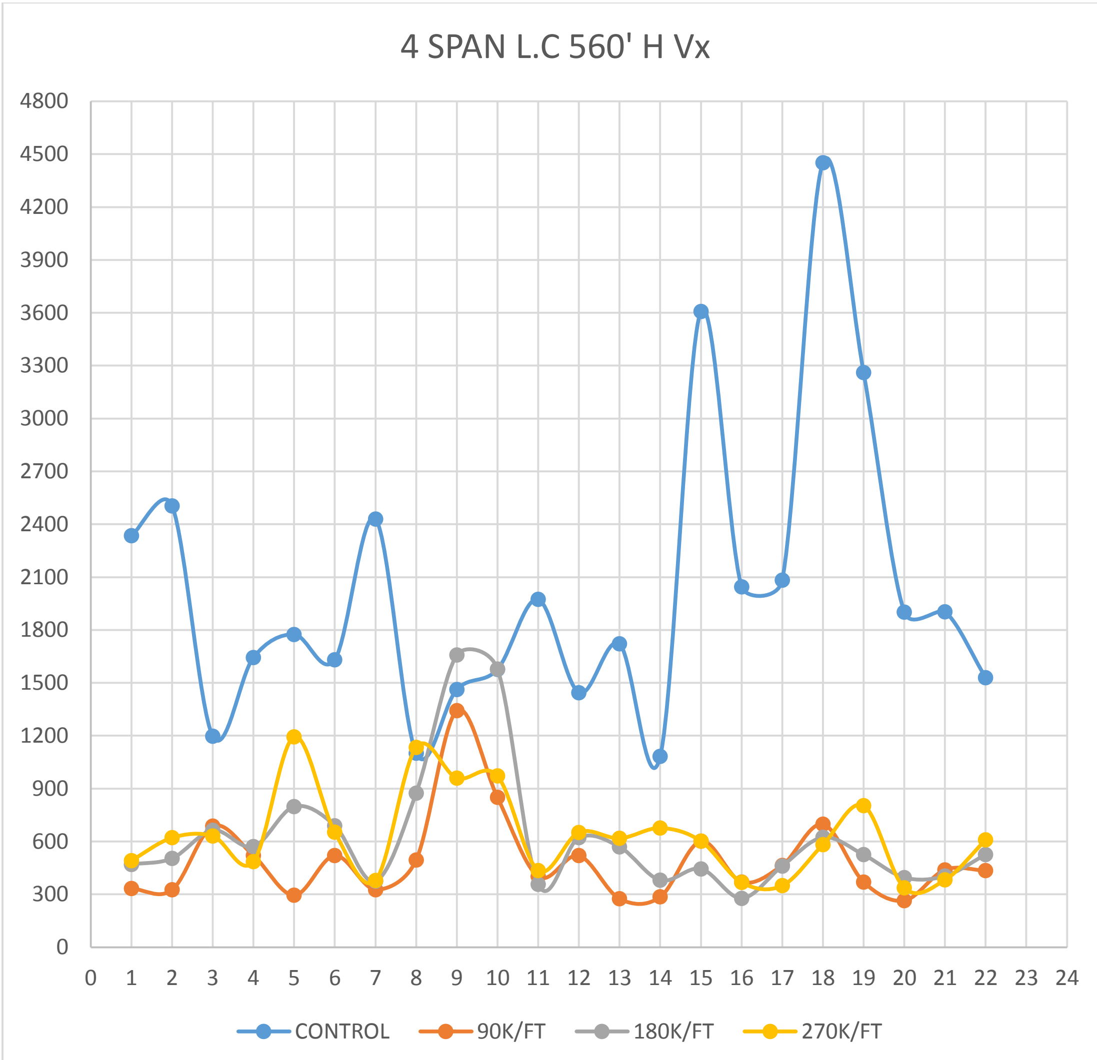


Fig. 4-109 Variation of longitudinal base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

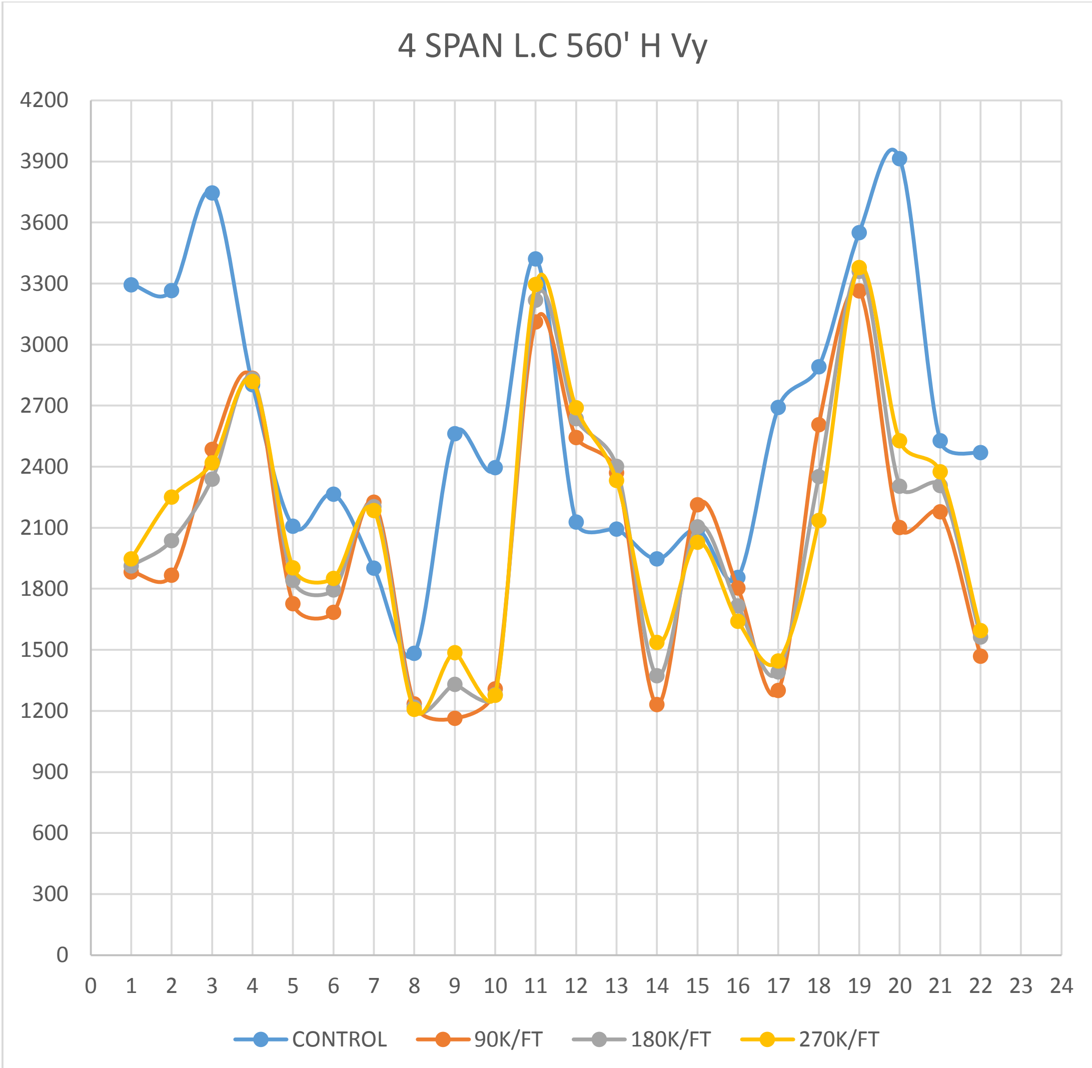


Fig. 4-110 Variation of transverse base shear with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

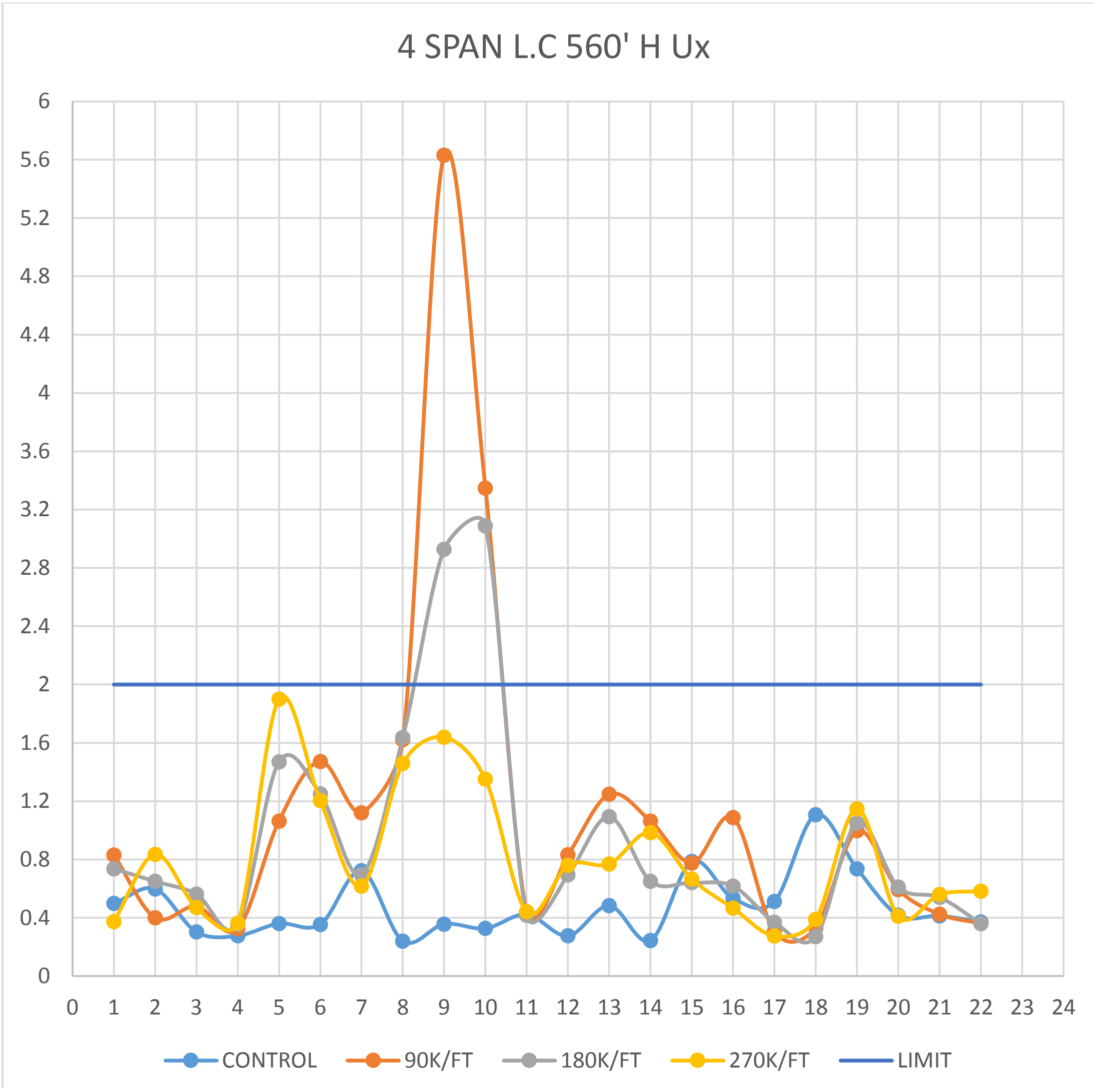


Fig. 4-111 Variation of longitudinal displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

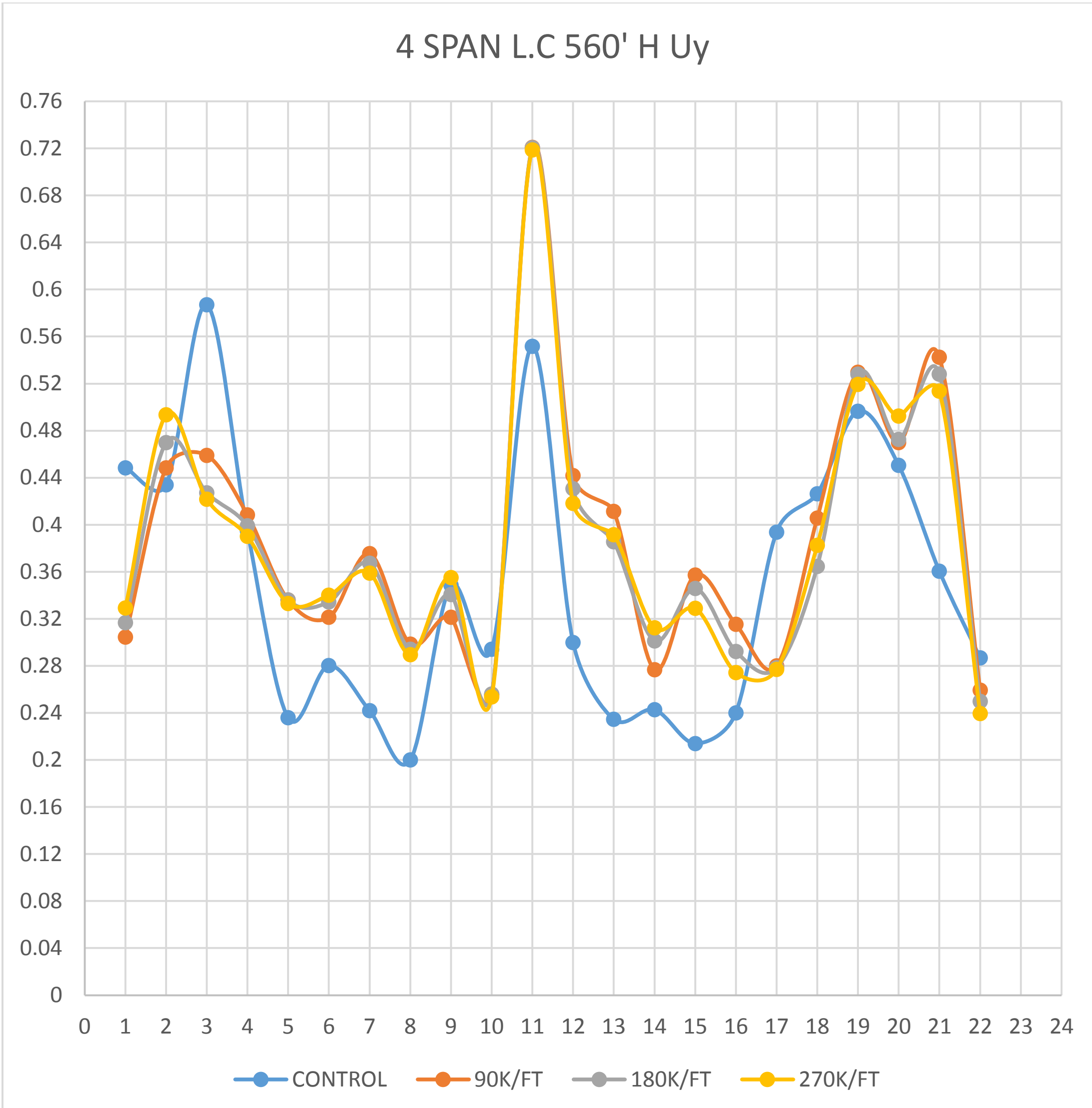


Fig. 4-112 Variation of transverse displacement with isolator stiffness for high intensity Far Field earthquakes, for the four span bridge.

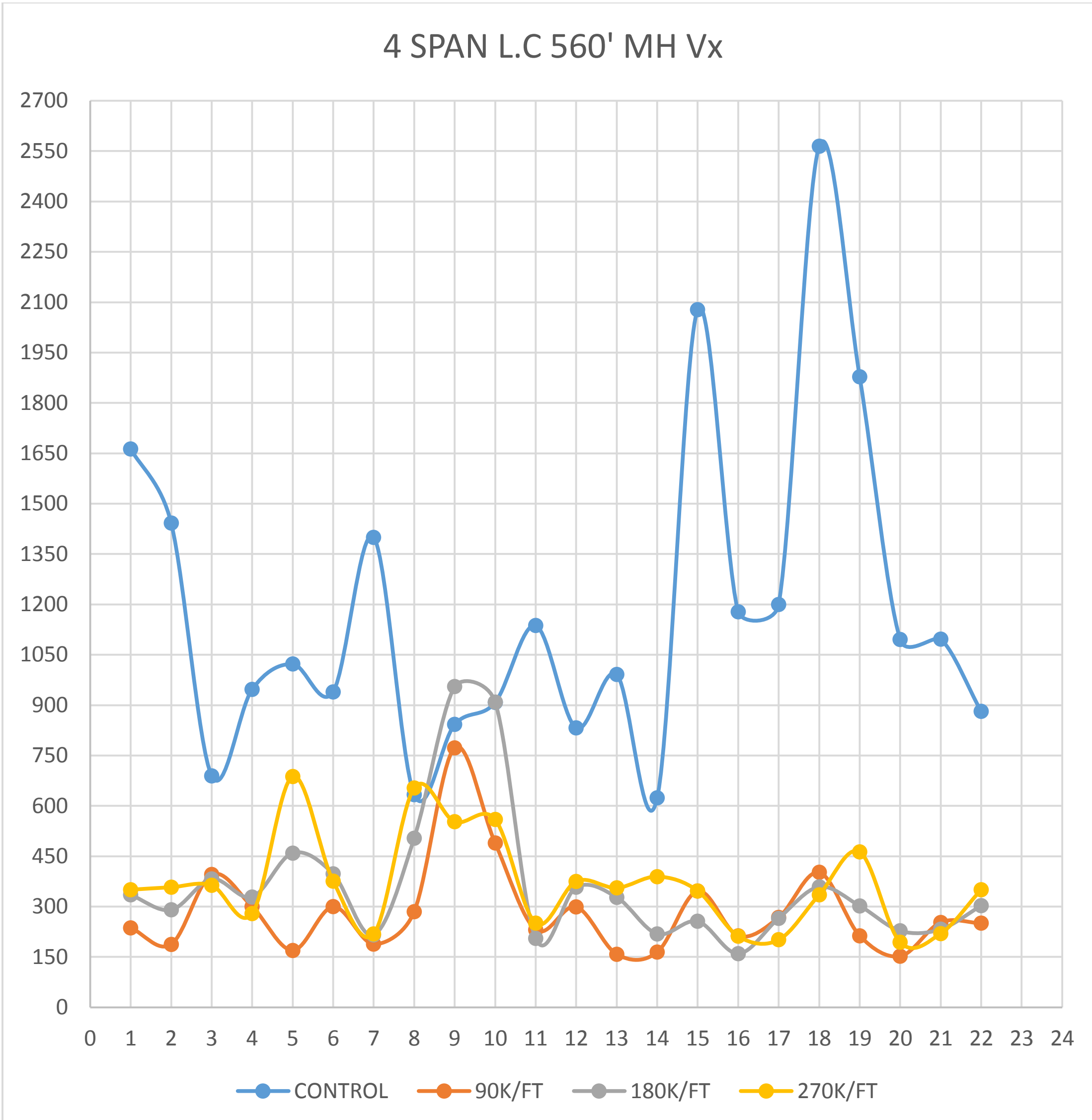


Fig. 4-113 Variation of longitudinal base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

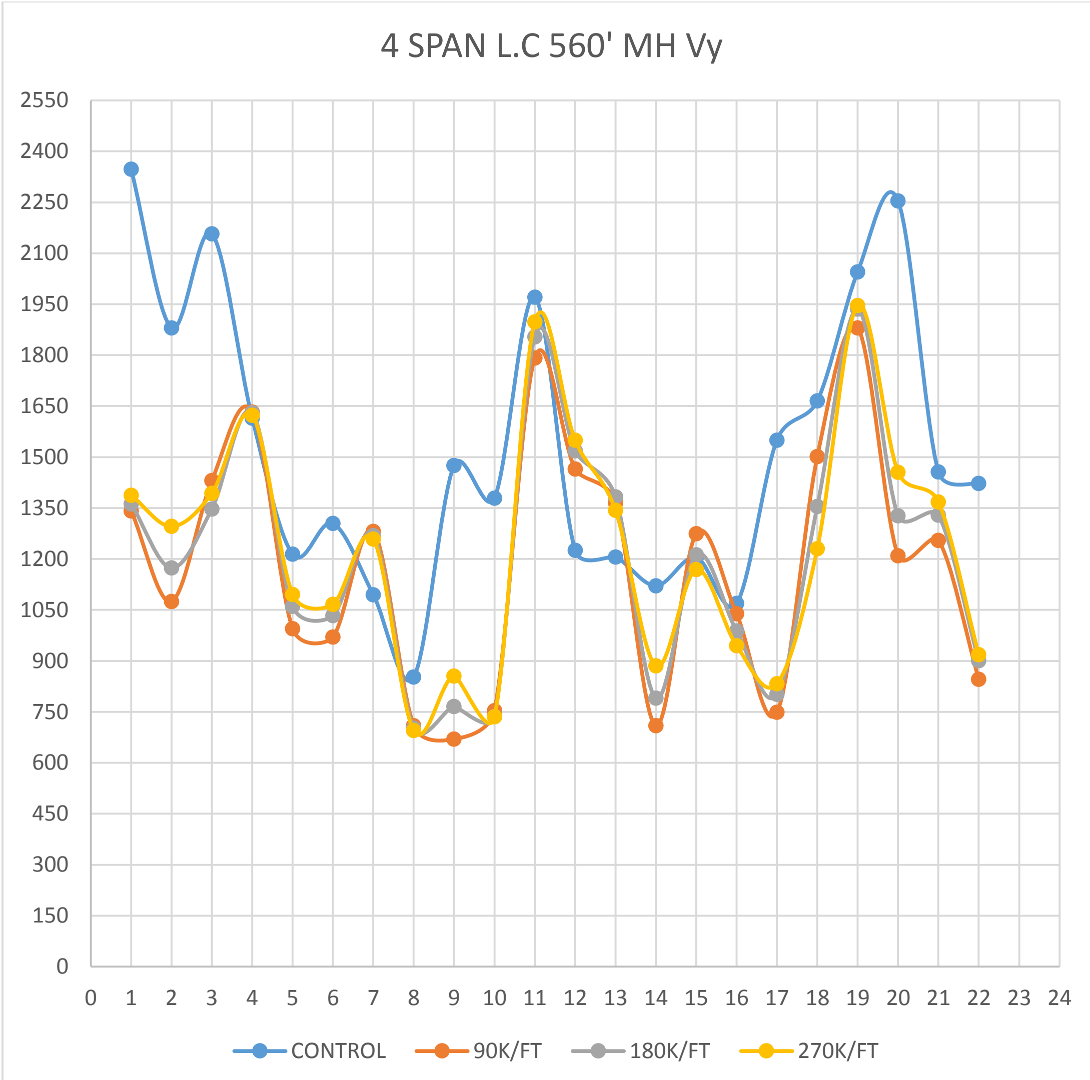


Fig. 4-114 Variation of transverse base shear with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

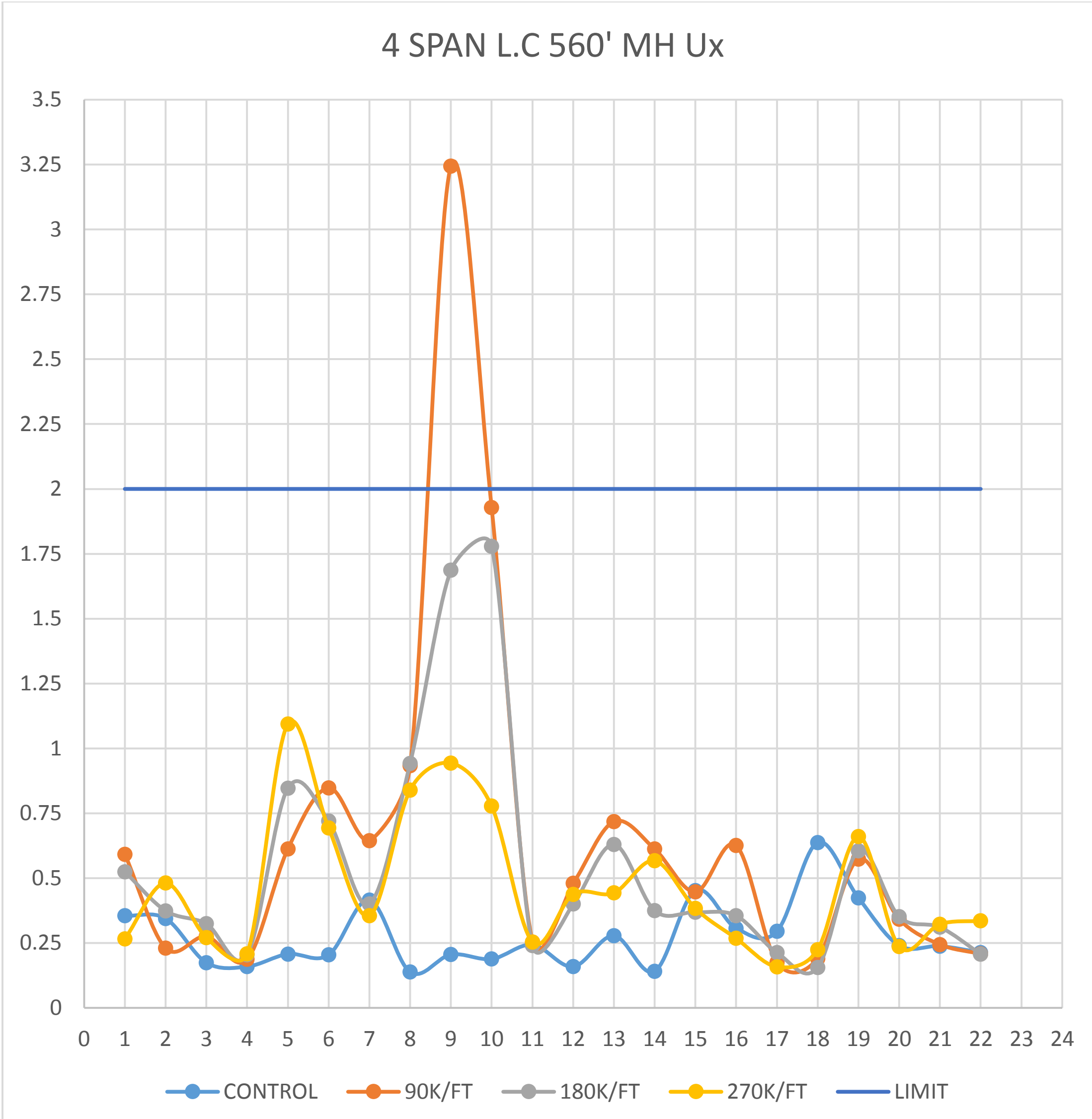


Fig. 4-115 Variation of longitudinal displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

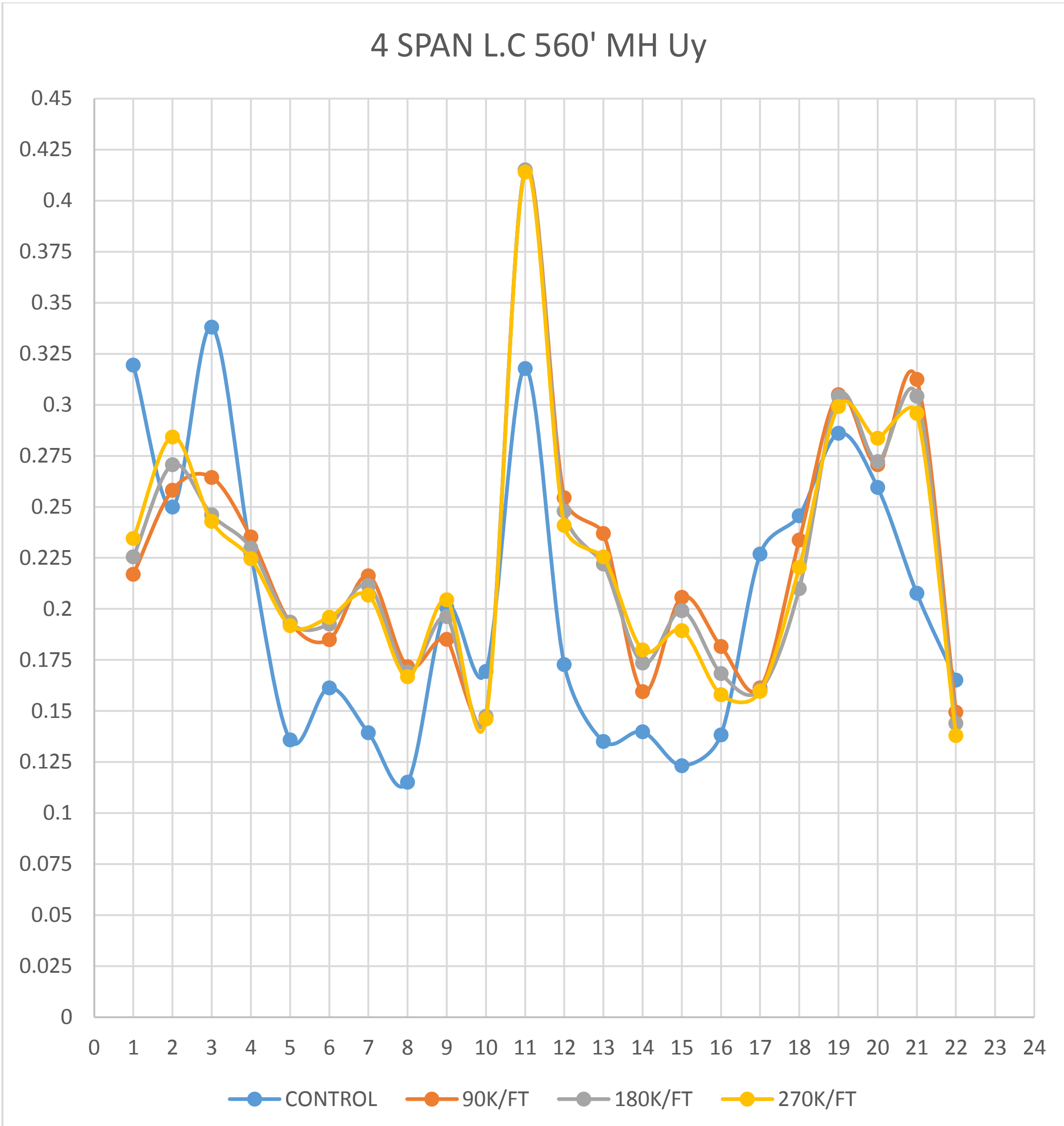


Fig. 4-116 Variation of transverse displacement with isolator stiffness for medium to high intensity Far Field earthquakes, for the four span bridge.

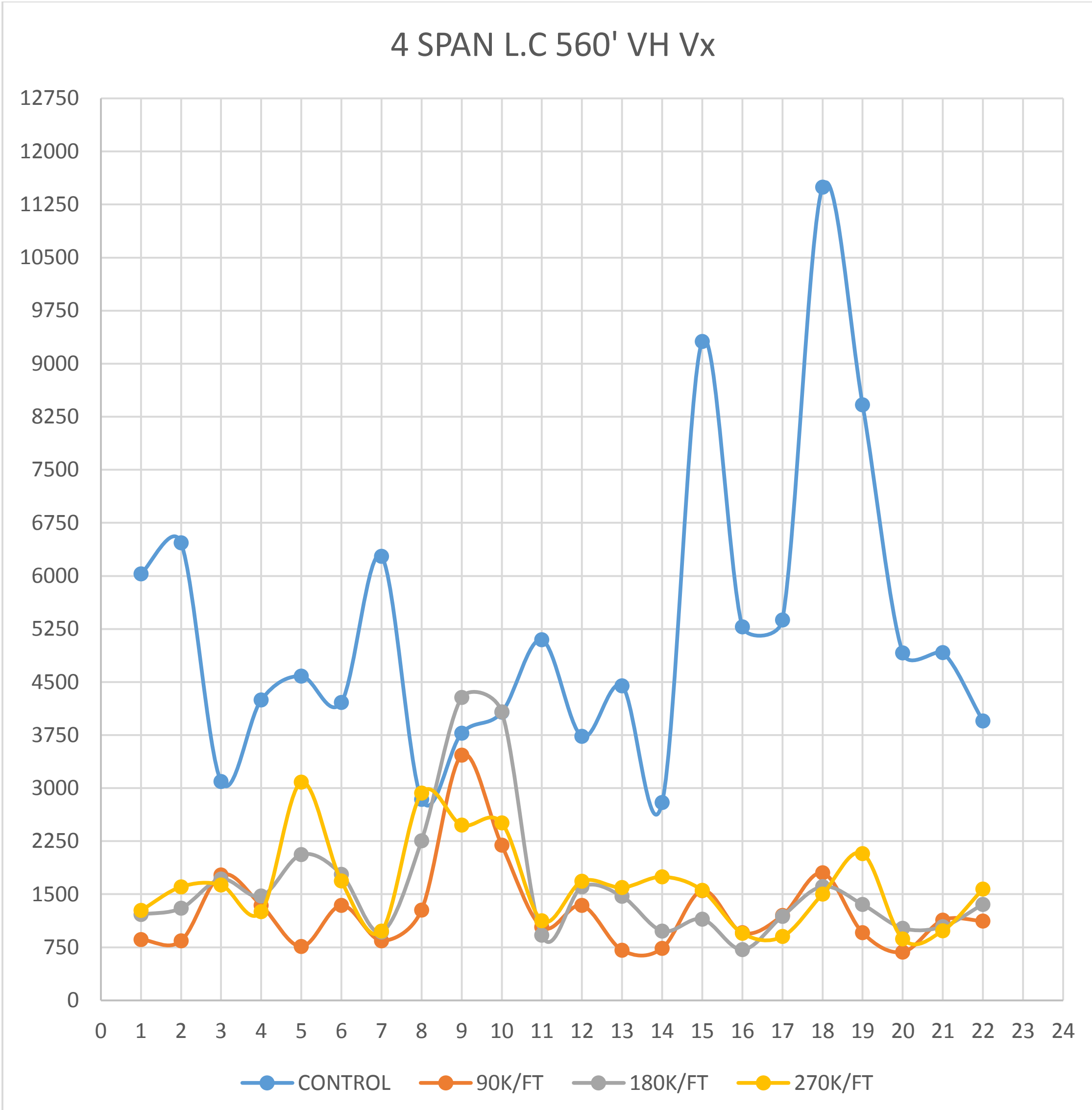


Fig. 4-117 Variation of longitudinal base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

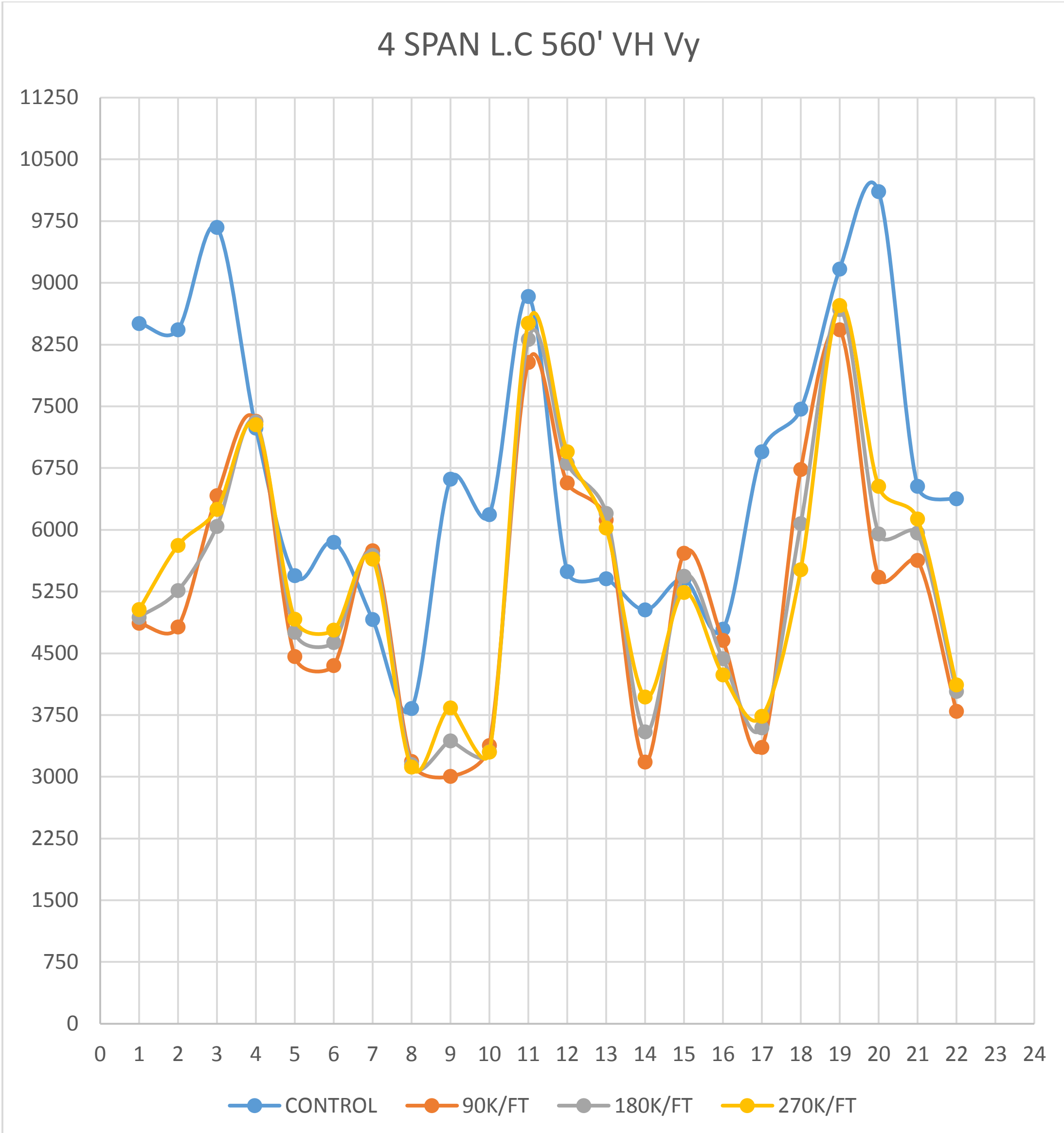


Fig. 4-118 Variation of transverse base shear with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

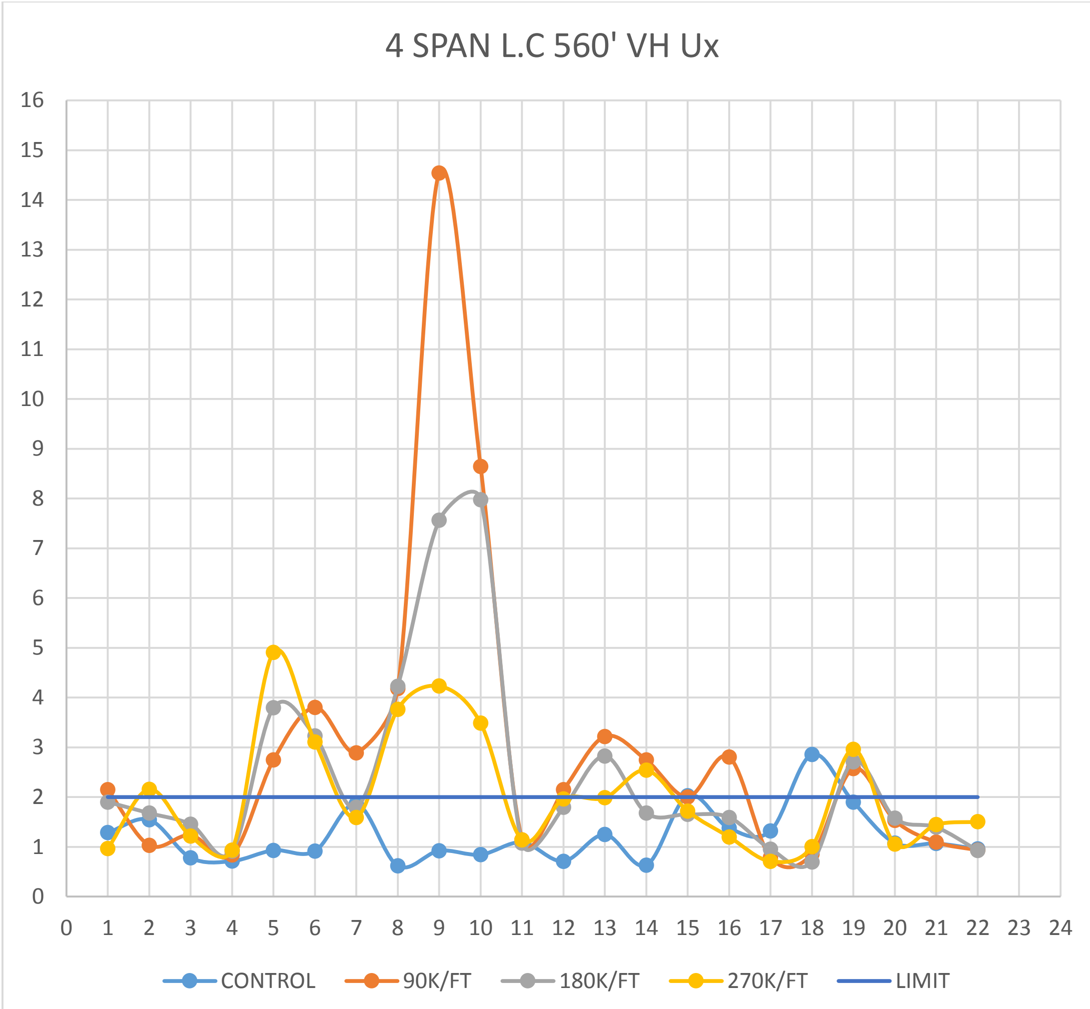


Fig. 4-119 Variation of longitudinal displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

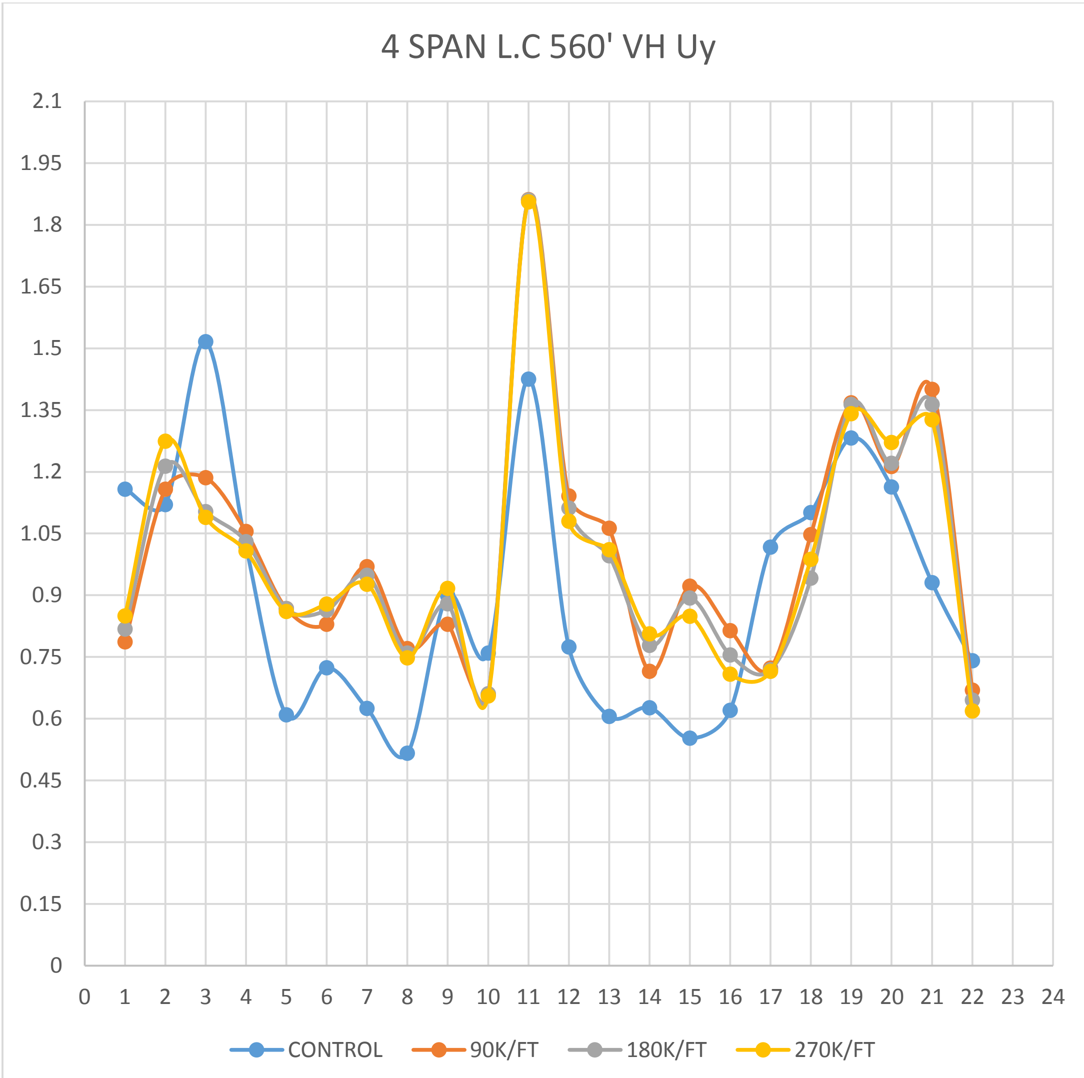


Fig. 4-120 Variation of transverse displacement with isolator stiffness for very high intensity Far Field earthquakes, for the four span bridge.

OBSERVATIONS:

In the cases where the base shears, with respect to 90, 180, and 270 kips per feet isolation stiffnesses, are greater than the control case is due to the usage of time history analysis rather than response spectrum analysis. In time history analysis the record is not smoothed out, hence it can lead to a fluctuation in the values of the spectral accelerations, which is why the base shear limits are exceeded. See Fig. 4-121.

Using isolator stiffness in the range of 90-180kips per feet leads to large longitudinal displacements, which can be minimized using dampers.

The longitudinal displacements caused by the earthquakes that were scaled to high intensities for the 4 span bridge show us that all three isolation stiffnesses (90, 180, and 270) can be used without the usage of any damping for most cases.

The longitudinal displacements caused by the earthquakes that were scaled to medium to high intensities for the 4 span bridge show us that 90, 180 and 270 kips per feet can be used as the stiffness of the isolator without the usage of any damping.

The longitudinal displacements caused by the earthquakes that were scaled to very high intensities for the 4 span bridge show us that while most earthquakes exceed the 2 feet limit for the displacement, the isolator stiffness should be equal to or greater than 270 kips per feet.

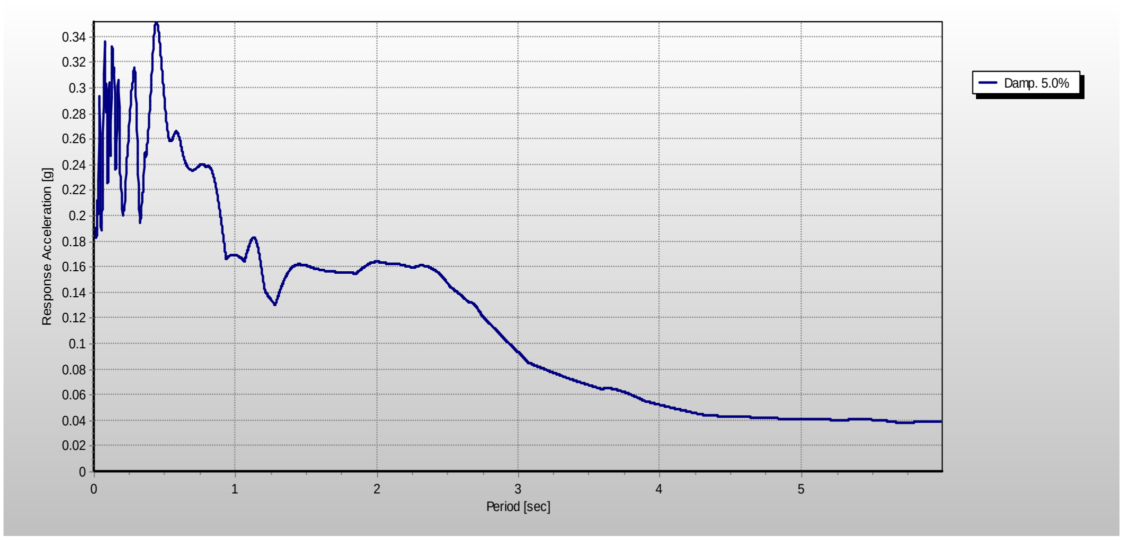


Fig. 4-121 Response curve of a typical Far Field earthquake record

The maximum longitudinal base shear values recorded for this case are:

Control = 11496.57

90 K/Ft = 3465.993

180 K/Ft = 4281.762

270 K/Ft = 3083.207

Table 4-2 Base shear reduction under Far Field Earthquake Loading

Bridge type	Maximum isolated base shear	Percentage Reduction
2 Span	1890.355	84.035
2 Span L.C	2021.834	41.345
3 Span 360'	2335.377	87.784
3 Span 400'	2940.713	85.695
3 Span L.C 360'	2666.131	64.549
3 Span L.C 400'	3108.629	60.295
4 Span 480'	3272.602	86.158
4 Span 560'	3761.436	87.684
4 Span L.C 480'	3155.885	67.911
4 Span L.C 560'	4281.762	62.756

Table 4-3 Base shear reduction under Near Field Earthquake Loading

Bridge type	Maximum isolated base shear	Percentage Reduction
2 Span	1634.116	81.887
2 Span L.C	1678.311	48.856
3 Span 360'	2607.083	86.93
3 Span 400'	2815.389	85.334
3 Span L.C 360'	2588.979	54.944
3 Span L.C 400'	2866.197	53.061
4 Span 480'	3603.03	87.819
4 Span 560'	4019.922	86.624
4 Span L.C 480'	3659.508	57.327
4 Span L.C 560'	3962.947	55.131

The results for the very high intensity far-field earthquakes scaled to the design spectrum show large displacements especially when isolators are used. However, for the Chi-Chi earthquake, the longitudinal displacements were excessively high when a 90k/ft stiff isolator was used. The Chi-Chi earthquake was a very big seismic event. Its elastic response spectrum when scaled to very high target spectrum (NGA number 1246), showed that the maximum displacement recorded exceeded 7 feet and the maximum PGV value exceeded 11ft/sec. Adding to that, the fact that isolators with a low initial stiffness of 90 kips per feet were used which made the displacements more excessive.

CHAPTER FIVE CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the results of this investigation, the following conclusions can be drawn:

1. The analysis results showed that when the earthquakes are scaled to very high intensities, isolators with large stiffnesses are needed to keep the displacements within the acceptable limit. Care should be taken when an isolator with larger stiffness value for the isolator is selected, because the system can generate high base shear, in which case the purpose of providing seismic isolation would be defeated.

2. It is noted that when the earthquake records are scaled to medium to high intensities the full range of isolator stiffnesses (90 k/ft to 270 k/ft) can be used without causing excessive longitudinal displacements and base shear.

3. For bridges subjected to high intensity earthquakes, the isolators should be carefully selected. This study showed that about 25% of the near field and 10% of the far field records exhibited excessive displacements which would require providing damping devices in the system.

4. Comparing the results of the near field and far field earthquake loading, it is observed that the maximum value of the base shear and displacement in the majority of cases occurred under far field earthquake loading. Many near field earthquake ground motions caused displacements exceeding 2 feet.

5. Comparing the results of the response to the near field and to the far field earthquake loading we observe that there is a greater reduction in base shear under far field earthquake loading, except in the case of the Two Span Bridge and the Four Span Bridge. Isolators with higher initial stiffness produced lower base shear under far field earthquake ground motions compared to near field earthquake ground motions, and there is a greater reduction in base shear when shorter columns are used.

5.2 RECOMMENDATIONS

The following recommendations are provided for further research in bridge isolation:

1. Further studies need to be carried out on other types of bridges such as curved bridges, and bridges with internal hinges.

2. Non-linear analysis, which takes into account the stiffness nonlinearity of the isolator, should be conducted to get more information on the behavior of the isolator under near field and far field earthquake ground motions.

3. Fixed support conditions were used in this study. However soil structure interactions need to be considered to understand better the role it plays in the seismic response of the structure and its effect on isolator behavior.

4. In cases where excessive displacements occur dampers have to be used and their non-linear behavior has to be accounted for as well.

CHAPTER SIX APPENDIX

This appendix contains sample response data that were used to plot the response of the bridge structures in Chapter 3 and Chapter 4.

Table 6-1 Sample Base Shear and Displacement values for a control case

Earthquake	Vx	Vy	U11	U22
VH-1116-FN	7578.687	2351.984	0.62556	0.04213
VH-1116-FP	5283.695	3409.403	0.517257	0.042997
VH-125-FN	11840.788	5128.175	1.056547	0.076557
VH-125-FP	6396.941	5715.546	0.594782	0.081153
VH-827-FN	2922.397	2134.895	0.235296	0.033798
VH-827-FP	2172.968	2085.437	0.24271	0.028533
VH-1158-FN	3356.68	2134.887	0.315251	0.036653
VH-1158-FP	4095.884	1976.143	0.373372	0.025284
VH-1246-FN	2590.542	1388.801	0.213839	0.011819
VH-1246-FP	2656.194	1064.419	0.212284	0.018476
VH-1602-FN	5506.83	3654.988	0.506703	0.036231
VH-1602-FP	7415.648	5276.081	0.687221	0.073446
VH-169-FN	4161.344	2129.339	0.396565	0.052177
VH-169-FP	3186.375	2182.487	0.273466	0.037317
VH-1787-FN	7338.145	4605.48	0.675081	0.060257
VH-1787-FP	3207.458	2790.822	0.279909	0.056869
VH-752-FN	6249.643	4579.33	0.60224	0.051359
VH-752-FP	7252.783	4642.715	0.565328	0.110883
VH-864-FN	4429.316	2924.724	0.369086	0.043845
VH-864-FP	4083.094	3057.019	0.31473	0.030916
VH-960-FN	6503.882	5263.542	0.622721	0.103352
VH-960-FP	8913.164	3614.482	0.756216	0.049176

Table 6-2 Sample Base Shear and Displacement values for a isolated bridge case

Earthquake	Vx	Vy	U11	U22
VH-1116-FN	176.197	2719.943	2.174997	0.066104
VH-1116-FP	157.99	3424.291	1.014681	0.059908
VH-125-FN	232.52	5843.201	1.16116	0.087873
VH-125-FP	194.963	5717.741	0.800698	0.131356
VH-827-FN	252	2252.272	2.358648	0.040796
VH-827-FP	436.308	1756.301	4.978476	0.036783
VH-1158-FN	283.067	2098.556	3.02149	0.050523
VH-1158-FP	520.059	1841.338	5.550809	0.027522
VH-1246-FN	1417.274	1426.816	14.604302	0.017776
VH-1246-FP	755.599	1224.179	8.930514	0.022367
VH-1602-FN	109.887	3670.341	1.01286	0.051656
VH-1602-FP	238.151	4020.927	2.071816	0.102302
VH-169-FN	219.899	2010.547	3.193063	0.055975
VH-169-FP	264.866	1707.449	3.271892	0.045882
VH-1787-FN	242.657	4357.303	2.255949	0.076945
VH-1787-FP	258.311	2979.616	3.141521	0.085325
VH-752-FN	189.59	4211.485	0.674026	0.081879
VH-752-FP	224.675	5130.745	1.000889	0.14117
VH-864-FN	274.146	3462.091	2.597839	0.061309
VH-864-FP	126.716	2795.658	1.47052	0.048438
VH-960-FN	211.521	5690.114	0.946626	0.142718
VH-960-FP	161.137	4741.506	0.955326	0.092398

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