# RESPONSE EVALUATION AND MODIFICATION OF TYPICAL BRIDGES IN THE CENTRAL AND SOUTHEASTERN UNITED STATES

**Reginald DESROCHES[1], Roberto LEON[2], Eunsoo CHOI[3], Tam T LAM[4], Shirley J DYKE[5] And Laura JANSEN[6]**

## SUMMARY

The seismic response of a multi-span simply supported bridge with steel bearings is studied. The analytical results of a nonlinear model of the bridge subjected to various ground motions show that the seismic demands on the non-ductile steel bearings would exceed their capacity causing failure of the bearings. Failure of the bearings can lead to large hinge displacements resulting in collapse of the bridge deck. Adding restrainers to the bridge slightly reduces the ductility demand on the piers. However, the restrainers increase the force in the bearings and abutments and are therefore not recommended as a means of retrofit for multi-span simply supported bridges with steel bearings. Replacing the steel bearings with elastomeric bearings significantly improves the performance of the bridge, although the deck displacements and relative hinge displacements are significantly increased. In addition, the large displacements in the deck produce large impact forces at the abutments. Retrofitting the bridge with restrainers reduces the large displacements in the deck and thus the impact forces at the abutments. However, the restrainers at the abutments impart large tensile forces at the abutments.

## INTRODUCTION

Bridges are key nodes in any transportation network, and field reconnaissance reports from past earthquakes indicate that many bridge failures could have been prevented with simple mitigation measures. While such mitigation measures have been successfully implemented in California, few similar efforts are underway in the central and southeastern United States, where multi-span simply supported (MSSS) bridges are common. Previous studies have found that the seismic performance of these bridges is generally not adequate (Dicleli and Bruneau, 1993). In particular, many of these bridges are supported on steel rocker bearings that lack adequate strength and ductility (Mander et al., 1996; Rashidi and Saadeghvaziri, 1997). These studies found that seismic demands on bearings generally exceed their capacity, resulting in failure of the bearings. The failure of the bearings reduces the demands on the columns, however, the hinge opening is increased. The other factors which control the response of the multi-span simply supported bridge are the column stiffness and strength, abutment stiffness and strength, and the available seat length.

Since most multi-span simply supported bridges are located in areas which have not been subjected to strong ground motion, few studies have looked at the effects of retrofitting these bridges. One common retrofit measure for bridges is to replace the steel rocker bearings with elastomeric bearings. Elastomeric bearings are designed to support large vertical loads, while providing only nominal resistance to large horizontal displacements. This set of conditions is ideal for isolating the vulnerable bridge substructure and allows for the easy accommodation of the thermal expansion of bridge decks. Another common retrofit measure is to connect the decks with restrainer cables. The California Department of Transportation (CALTRANS) began using cable restrainers after the 1971 San Fernando earthquake showed that bridges are vulnerable to collapse due to unseating at hinges (Jennings, 1971). The restrainers, which are typically connected from one deck to another, through the diaphragm, can significantly reduce the hinge displacement between decks (DesRoches and Fenves, 1999).

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[1] *Assistant Professor, Georgia Institute of Technology, School of Civil & Environmental Eng., Atlanta, GA 30332-0355, USA*
[2] *Professor, Georgia Institute of Technology, School of Civil & Environmental Engineering*
[3] *Graduate Student Researcher, Georgia Institute of Technology, School of Civil & Environmental Engineering*
[4] *Graduate Student Researcher, Georgia Institute of Technology, School of Civil & Environmental Engineering*
[5] *Assistant Professor, Washington University, Department of Civil Engineering*
[6] *Graduate Student Researcher, Washington University, Department of Civil Engineering*

However, the restrainers can also transfer large forces to adjacent frames, which are not typically assumed in design.

In this study, nonlinear dynamic analyses are performed to evaluate the seismic characteristics of multi-span bridges subjected to ground motion expected in the Central and Southeastern United States. Nonlinear models of the bearings, abutments, and columns are developed to assess the performance of the bridge due to strong ground motion. After identifying the critical components of the bridge, several retrofit measures such as of replacing steel bearings with elastomeric bearings and connecting the decks with restrainers are analytically evaluated.

## BRIDGE PROPERTIES AND MODELING

The multi-span simply supported bridge (MSSS) typically has 2-4 lanes, with 2-5 spans ranging in length from 30-100 ft. The decks are typically reinforced concrete slabs on steel or prestressed concrete girders. The fixed and expansion bearings are typically alternated, as shown in Figure 1. The bridge girders are supported on a single or multi-column bent, and the abutment types vary depending on bridge and foundation characteristics.

Nonlinear dynamic analyses of a 2 dimensional model of a typical multi-span bridge shown in Figure 1 are conducted using DRAIN-3DX (Prakash et al., 1993). Full composite action between the deck-slab and steel girders is assumed. The superstructure is modelled using linear elastic elements, since it is expected that the deck will remain linear for the cases considered, as shown in Figure 2.

The bridge consists of several sets of steel rocker bearings and steel high type fixed bearings. Experimental tests of steel bearings similar to those in the bridge were conducted by Mander et al. (1996). The force-deformation relationships from those tests were used to develop analytical steel bearing elements for this study. The rocker bearing resists forces from a combination of rolling resistance at the base of the rocker and Coulomb friction at the hinge of the sole plate-rocker interface. This combination of forces produces a bilinear hysteretic behaviour with the yield force equal to the Coulomb friction force. For the analytical model of the rocker bearing, a bilinear element was used with initial stiffness, $K_e$=80 kips/in, 1.8% strain hardening, and a yield force equal to 2.5 kips. Experimental tests of fixed steel bearings show that the behaviour is governed by the prying action of the masonry plate on the rubber pad bedding, bond failure of the anchor bolts, and rocking of the bearing on the pedestal (Mander et al, 1996), resulting in the force deformation relationship shown in Figure 3. To represent this complex behaviour, a nonlinear link element is used in parallel with bilinear truss element. The initial stiffness of the bearing, $K_1$, is 1022 kips/in with a yield displacement of .03 inches.

The abutment properties used in this model are based on a combination of design recommendations from CALTRANS (1990) and experimental tests of abutments (Maroney et al., 1993). The abutment can resist forces in both compression (passive stiffness) or in tension (active stiffness). The passive stiffness recommended by the Caltrans Bridge Design Manual (1990) is 200 kips/in/ per foot of backwall. Recent experimental tests suggest that this may overestimate the stiffness and therefore should be reduced by a factor of 0.40. The ultimate strength is typically taken as 530 x H, where H is the height of the abutment. For the bridge considered, the stiffness and ultimate strength of the abutments are 5504 kips/in and 4238 kips, respectively. There are three yielding points in the passive behaviour of abutments, $D_{y1}$ = .005H, $D_{y2}$ = 0.015H, and $D_{y3}$=0.06H. The corresponding stiffnesses are $K_{1p} = K_p$, $K_{2p} = 0.13K_p$, and $K_{3p} = 0.039K_p$. The active abutment stiffness is a function of the number of piles activated. Caltrans suggests using an effective active stiffness of 40 kips/in x P, where P is the number of piles. The ultimate strength of the abutment in active action is approximately 25 x P. For this bridge the active abutment stiffness and strength are 720 kips/in and 450 kips, respectively. The combined active and passive behaviour of the abutment is shown in Figure 3.

An impact element is used to model the pounding between two decks in the bridge. The compression-only tri-linear gap element has springs that penalise closing of the gap. The springs are assigned increasing stiffness which is approximately the same order of magnitude as the axial stiffness of the deck. The 4-inch gap represents the distance between adjacent decks.

For the analysis of the retrofitted structure, steel bearings are replaced with elastomeric bearings and/or restrainer cables are added to the intermediate hinge at the decks. The elastomeric bearings can be modelled with a bilinear element based on three parameters, $K_1$, $K_2$, and Q, as shown in Figure (Kelly, 1997). The parameters $K_1$, $K_2$, and Q are a function of the bearing type and size. For the bearings used in this study, $K_1$=10.44 kips/in, and $K_2$ = 3.48 kips/in. The stiffness of the tension-only elements for the restrainer cables is based on the specified cross-sectional area of the cables, modulus of elasticity of 10,000 ksi, and length of the cable.

Restrainers typically have a slack to allow for thermal expansion without producing a force in the restrainers. For this study, the total stiffness of the restrainers is 200 kips/in with a slack of 0.50 inches.

## RESULTS

To assess the performance of the multi-span simply supported bridge, the nonlinear model above is subjected to several levels of ground motion. Because few ground motion records of magnitude greater than 5 exist in Mid-America, synthetic ground motion records which are representative of the Mid-America region have been generated for this study (Herrman and Akinci, 1999). Two sets of ground motion representing two magnitude levels are generated. The first set of ground motions is generated for a magnitude 6.5, and is scaled to a PGA of 0.40g. The second set of ground motion is generated for a magnitude 7.5 earthquake and is scaled to a PGA of 0.70g. Both ground motion records are based on a Mid-America deep soil profile with a depth of 500 m, and a distance from the site of 65 km. For the analytical studies of the bridge, 5 synthetic ground motion records were generated for the M=6.5 and M=7.5 earthquakes. The bridge response is evaluated for the 5 records and the mean response is recorded. The mean response spectra for both earthquakes are shown in Figure 4.

Table 1 lists the response quantities of the existing steel bearing bridges subjected to two levels of ground motion. In addition, the bridge response quantities are evaluated for the case where the bridge has been retrofitted. The three retrofit strategies are (1) adding restrainers at the decks and abutments in the existing steel bearing bridge, (2) replacing the steel bearings with elastomeric bearings, and (3) adding restrainers at the deck and abutments in bridges with elastomeric bearings. The response quantities of interests are: pier ductilities, $\mu_i$, fixed bearing deformations, $\Delta_{Bi}$, hinge displacements, $\Delta_i$, and abutment forces in compression and tension, $F_{ac}$, $F_{at}$.

For the existing steel bearing bridge, the 0.40g ground motion produced yielding in the piers ($\mu$=2.2) and hinge openings ranging from 1.02 in to 2.46 in. The pier ductility is defined by the ratio of the pier displacement to the pier displacement at first yield in the bi-linear moment curvature relationship for the piers. The hinge opening is defined as the relative displacement between the peir and the end of the deck. Bearing 1 had a deformation of 0.15 in, which indicates it has yielded, but most likely has not failed. The abutment forces were well within the range for exceptable response. Overall, the bridge performed adequately for this level of ground motion. For the 0.70g ground motion, the piers would have ductility demands of 6.4 and 5.0 in piers 1 and 2 respectively. Bearing 1 would have a deformation of 0.92 inches, which would most likely fracture the bearing. Bearing 2 has well exceeded it's yield deformation and may also be unstable. The hinge opening at the first and third piers exceeded the allowable seat width of 4 inches, which would result in the collapse of those spans. The abutment forces were less than the allowable forces.

The existing steel bridge is retrofitted with cable restrainers and evaluated for the same set of ground motions. For the case with 0.40g the pier ductility demands are reduced compared to the case without restrainers. Similarly, the hinge opening is reduced for piers 1 and 3 and slightly increased for pier 2. However, the deformation of bearing 1, located at the first abutment, is twice as large as the case without restrainers. The restrainer connection at the hinges provides continuity to the MSSS bridge and allows the spans to move together. This produces large inertia forces in the first span which is transmitted to the fixed bearing at the abutment. The increased force in the fixed bearing is transferred to the abutment in active action (tension). The tension force in abutment 1 increased 50% compared to the case without restrainers. The tension force in abutment 2 also increases because of the restrainer pulling at abutment 2. Similar conclusions can be made with the 0.70g ground motion.

An analysis is conducted with the nonductile steel bearings replaced with elastomeric bearings. The analysis shows that the elastomeric bearings significantly reduce the demands on the columns compared to the case with steel bearings. The elastomeric bearings have a low horizontal stiffness which isolates the substructure from the forces in the superstructure. However, the flexible elastomeric bearings produce large hinge displacements in the bridge decks. For the case with 0.70g ground motion the displacements at both piers exceed the allowable displacement to prevent unseating. In addition, large compression forces are obtained at the abutments due to impact of the end spans with the abutments.

Finally, restrainers are added to the bridge with elastomeric bearings. As expected the restrainers are effective in reducing both the hinge displacements and column ductility compared with the case without restrainers. In addition, the restrainers are effective in reducing the compression forces in the abutments. However, the restrainers considerably increase the tension force in the abutments. The restrainers are attached directly at the abutments which allows for a direct transfer of the inertia forces from the deck to the abutment in tension.

## EXPERIMENTAL TESTS OF STEEL BEARINGS AND CABLE RESTRAINERS

Bridges with steel bearings are commonly used in the Central, Eastern, and Southern United States. Since very few have been subjected to strong ground motion, their seismic characteristics are not well understood. A recent study tested steel bearings typically found in the eastern part of the United States (Mander et al, 1996). Several types of bearings, including fixed and rocker bearings, were tested to failure to determine their force-deformation characteristics. The study found that steel bearings are particularly vulnerable to damage due to earthquakes. Several retrofit strategies such as increasing the keeper plates or embedding the existing bearing in concrete were recommended.

Similarly, few experimental studies on restrainer cables have been conducted. The only experimental test to date of restrainer cables was conducted by Selna (1989). Selna conducted an experimental evaluation of the strength, stiffness, and cyclic load-deflection behaviour of a full-scale section of an intermediate hinge with longitudinal restrainer cables. A representative portion of a reinforced concrete box girder bridge which included the hinge was constructed and tests were performed to determine the force-deformation relationship of the reinforced concrete box girder with a restrainer. The study found that the restrainer components failed prior to reaching the design strength of the cable. In addition failure of the box girder may occur before the restrainer fails.

The bearings and cable restrainers commonly used in Mid-America are different from those which have been previously tested. Therefore, to assess their seismic characteristics, a full-scale model of a section of a steel girder bridge will be tested under pseudo-dynamic loading. The model bridge is based on an existing steel girder bridge in Tennessee, which has been considered for seismic retrofitting with cable restrainers. The two main girders are W30x292 beams that span 40’-0” at a distance of 7’-7 ½” between girder centerlines. Transverse stiffener beams (W30x124) are spaced between the main girders so that the loading of the bridge will remain in-plane and thus, prevent torsional effects. The weight of the bridge will be modeled by casting a large concrete block between the main girders. The superstructure of the bridge, described above, will rest on top of bearings which will rest on pier caps anchored to the floor. The piers are designed so that the reinforcement is similar to that on actual bridges in order to accurately predict the behaviour of the restrainer cable connections at the pier caps. The bridge will be loaded with a force history obtained from an analytical study of the bridge subjected to strong ground motion. The loading of the model bridge is achieved through the use of an MTS Actuator Type 243.45 with a maximum average speed capacity of approximately 12 in/sec, with 100 kips in tension, and 146 kips in compression. The actuator is attached to a structural wall and to the concrete block.

The main goal of the test, to be performed in November, 1999, is to evaluate the effectiveness of various bearings and cable restrainers during a seismic event, and to verify the existing models for bearings and cable restrainers. Several types of bearings and restrainers will be tested under various loading conditions.

## CONCLUSIONS

A nonlinear dynamic analysis of a multi-span simply supported bridge with steel bearings found that the seismic demands on the non-ductile steel bearings would exceed their capacity causing failure of the bearings. Failure of the bearings will also lead to large hinge displacements resulting in collapse of the bridge deck. Adding restrainers to the bridge slightly improves the ductility demand on the piers, however, the restrainers increase the force in the bearings and abutments and are therefore not recommended as a means of retrofit for steel bearing bridges. Replacing the steel bearings with elastomeric bearings significantly improves the performance of the bridge. The elastomeric bearings reduce the demands on the columns. However, the hinge and deck displacements are significantly increased. In addition, the large displacements in the deck produce large impact forces at the abutments. Finally, the performance of the bridge with elastomeric bearings and restrainers is evaluated. The restrainers are effective in limiting the large displacements in the deck and thus the impact forces at the abutments. However, the restrainers impart large tensile forces at the abutments. Since the passive (tensile) strength of the abutments is considerably less than that in compression, the ultimate force is easily exceeded.

Based on the results from this study, it is recommended that structures being retrofitted with elastomeric bearings should be provided with restrainers to limit the hinge displacements. However, the stiffness and strength of the restrainers should be limited as not to exceed the tensile strength of the abutments.

## ACKNOWLEDGEMENTS

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## Table 1 : Response of Multi-Span Simply Supported Bridge to Synthetic Ground Motion

| Bridge Type[1] | PGA (g) | Bearing Deformation (inches) | | | | | | Pier Ductility[2] | | Hinge Opening[3] (inches) | | | | Abutment Force (kips) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta_{B1}$ | $\Delta_{B2}$ | $\Delta_{B3}$ | $\Delta_{B4}$ | $\Delta_{B5}$ | $\Delta_{B6}$ | $\mu_1$ | $\mu_2$ | $\Delta_1$ | $\Delta_2$ | $\Delta_3$ | $\Delta_4$ | $F_{1t}$ | $F_{1c}$ | $F_{2t}$ | $F_{2c}$ |
| SB | 0.40 | .15 | 2.5 | .03 | 1.0 | .01 | 2.0 | 2.2 | 1.2 | 2.5 | .03 | 1.0 | .01 | 236 | 264 | 40 | 37 |
| SB-R | 0.40 | .31 | 1.6 | .02 | 1.4 | .01 | 1.4 | 1.3 | .88 | 1.6 | .02 | 1.4 | .01 | 354 | 256 | 211 | 35 |
| EB | 0.40 | 2.3 | .81 | 3.2 | 3.2 | .94 | 1.8 | .77 | .77 | .81 | 3.2 | 3.2 | .94 | 85 | 75 | 72 | 86 |
| EB-R | 0.40 | 1.8 | .81 | 2.4 | 2.4 | .94 | 1.8 | 1.0 | .97 | .81 | 2.4 | 2.4 | .94 | 331 | 168 | 326 | 92 |
| SB | 0.70 | **.92** | 5.1 | .30 | 2.0 | .05 | 4.1 | 6.4 | 5.0 | **5.1** | .30 | 2.0 | .05 | 375 | 530 | 68 | 394 |
| SB-R | 0.70 | **1.0** | 2.5 | .08 | 2.2 | .04 | 2.2 | 5.5 | 4.2 | 2.5 | .08 | 2.2 | .04 | **500** | 581 | 379 | 403 |
| EB | 0.70 | 5.0 | 2.3 | 5.3 | 5.1 | 2.0 | 5.1 | 4.0 | 3.9 | 2.3 | **5.3** | **5.1** | 2.0 | 161 | 2425 | 164 | 2364 |
| EB-R | 0.70 | 2.5 | 1.9 | 4.4 | 4.0 | 1.7 | 2.5 | 3.2 | 3.6 | 1.9 | **4.4** | 4.0 | 1.7 | **500** | 1396 | **500** | 1321 |

**Bold** – Indicates response quantities that exceed their capacity.

[1] SB = Steel Bearing, SB-R = Steel Bearing w/ restrainer, EB = Elastomeric Bearing, EB-R = Elastomeric Bearing w/ restrainer

[2] Pier ductility based on idealized bilinear moment curvature relationship for piers

[3] Hinge opening defined as relative displacement between deck and pier.

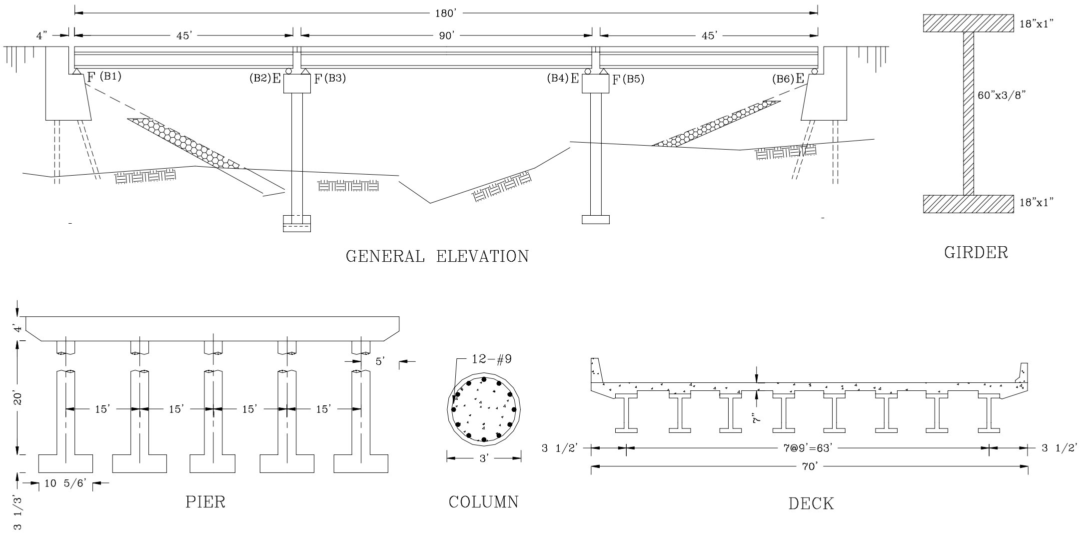


**Figure 1 : Typical Multi-Span Simply Supported Bridge with Steel Bearings.**

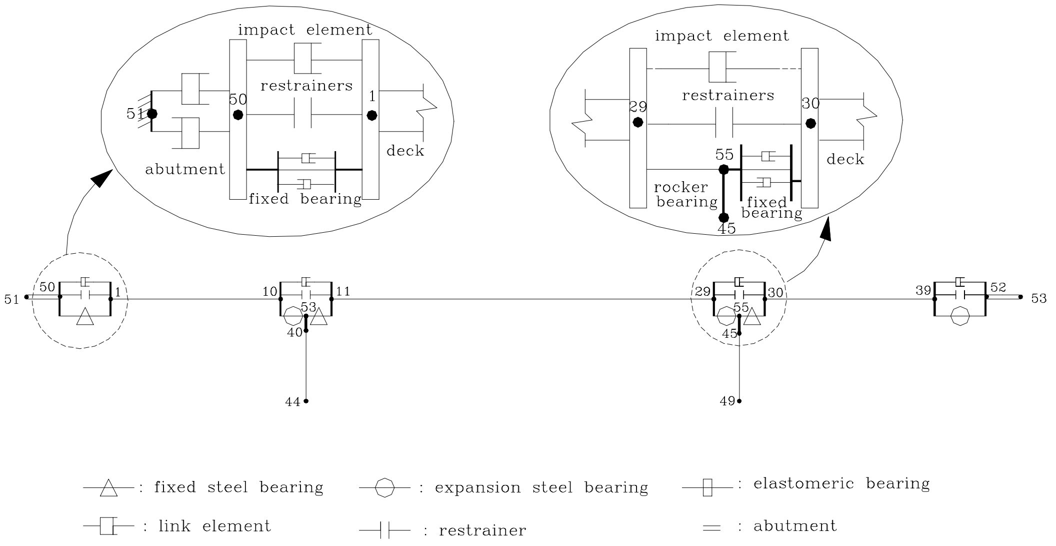
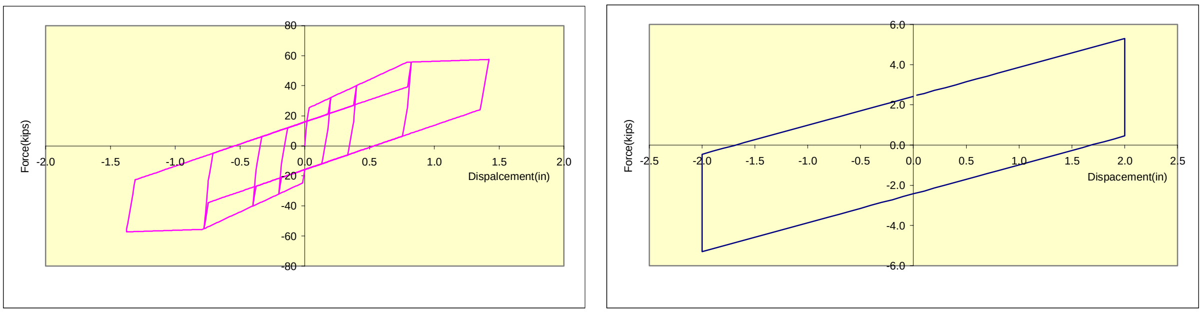
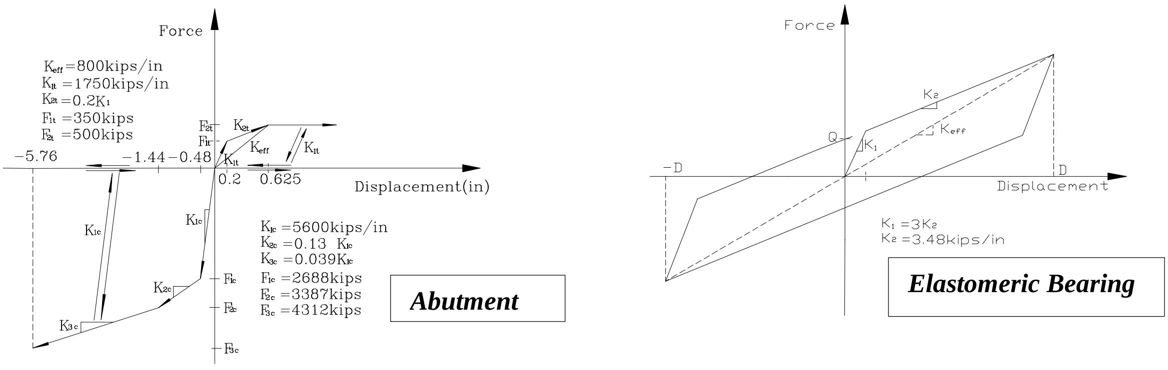


Figure 2: Nonlinear Analytical Model of Multi-Span Simply Supported Bridge with Steel Bearings.



***Fixed Steel Bearing***

***Expansion Steel Bearing***



***Abutment***

***Elastomeric Bearing***

Figure 3: Force-Displacement Relationships for Fixed Steel Bearings (Top Left), Expansion Steel Bearings (Top Right), Abutments (Bottom Left), and Elastomeric Bearings (Bottom Right).

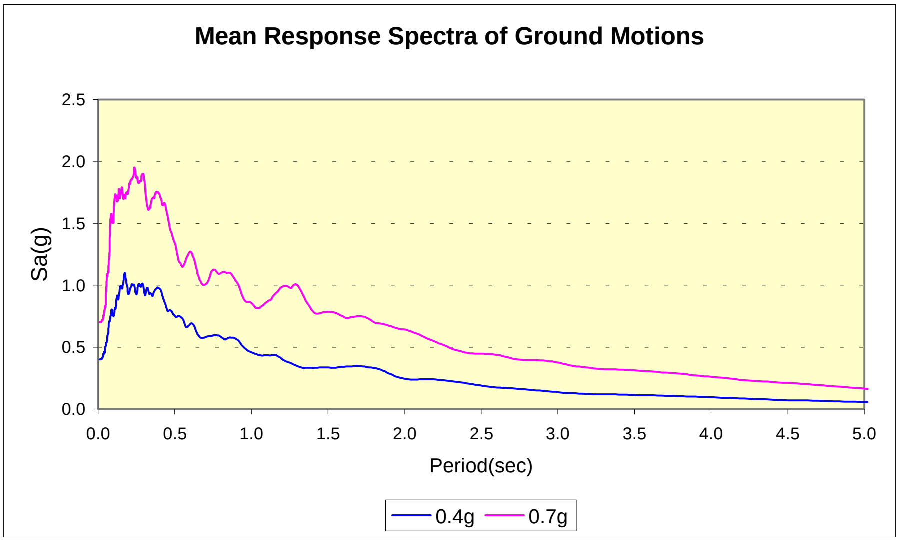


**Figure 4: Mean Response Spectra of Synthetic Ground Motions Used in Analytical Study.**

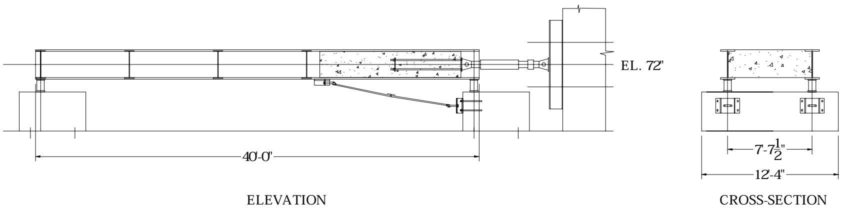


**Figure 5: Experimental Setup for Tests of Restrainer Cables and Bearings.**