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저감장치에 의해 개선된 고속도로 다경간 강교량의 지진응답

Seismic Responses of Highway Multiple Span Steel Bridges Retrofitted by Protective Devices

최 은 수*　　　김 주 우**
Choi, Eun-Soo　　　Kim, Joo-Woo

요 약

이전 논문에서 미 중부 및 동남부 지역의 전형적인 다경간 단순교와 다경간 강거더 연속교의 지진 응답을 연구하였으며, 이런 교량에서 덱 사이의 충돌과 큰 연성이 요구되는 기둥은 취약하여 손상을 입을 수 있다는 것을 보여주었다. 더구나, 고정 및 가동 교조장치는 강한 지진운동에 쉽게 피해를 입을 수 있다. 이 논문에서는 몇 개의 개선된 고무 베어링, 납-고무 베어링 그리고 제지선을 사용하여 전형적인 다경간 단순교와 다경간 강거더 연속교의 지진 응답을 평가하였다. 납-고무 베어링은 지진에 취약한 전형적인 교량의 응답을 개선하는데 효과적인 방법으로 평가되었다. 고무 베어링은 기둥의 요구량을 줄이지만, 다경간 단순교 강거더 교량에서 덱 사이의 강한 충돌을 유발시킨다. 제지선은 일반적으로 사용되지만 다경간 단순교와 다경간 연속교의 지진에 대한 손상을 절감하는데 중간정도의 효과를 보여주었다.

Abstract

A previous study evaluated the seismic response of typical multi-span simply supported (MSSS) and multi-span continuous (MSC) steel-girder bridges in the central and southeastern United States. The results showed that the bridges were vulnerable to damage resulting from impact between decks, and large ductility demands on nonductile columns. Furthermore, fixed and expansion bearings were likely to fail during strong ground motion. In this paper, several retrofit measures to improve the seismic performance of typical multi-span simply supported and multi-span continuous steel girder bridges are evaluated, including the use of elastomeric bearings, lead-rubber bearings, and restrainer cables. It is determined that lead-rubber bearings are the most effective retrofit measure for reducing the seismic vulnerability of typical bridges. While isolation provided by elastomeric bearings limits the forces into the columns, the added flexibility results in pounding between decks in the MSSS steel-girder bridge. Restrainer cables, which are becoming a common retrofit measure, are only moderately effective in reducing the seismic vulnerability of MSSS and MSC steel girder bridges.

keywords : seismic performance, bridge, retrofit, elastomeric bearing, lead-rubber bearing, restrainer cable

1. INTRODUCTION

The results of the analysis of the MSSS and MSC steel bridges illustrate that these bridges are vulnerable to damage during seismic loading[1]. The vulnerabilities include damage to nonductile columns, failure to fixed steel bearings, instability of expansion (rocker) bearings, and damage to abutments. In addition, bridges with short seat widths are susceptible to collapse due to unseating. To increase the seismic resistance of the typical MSSS and MSC steel bridges, seismic retrofit measures must be performed. While seismic retrofit of bridges has been performed for

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* 한국철도기술연구원 궤도노반팀 선임연구원, 공학박사
Tel : 031-461-8351,　Fax : 031-460-5359
E-mail : eunsoochoi@krri.re.kr
** 정회원 · 세명대학교 건축공학과 조교수, 공학박사
E-mail : jw_kim@semyung.ac.kr

many years in California and other parts of the west coast, many states in the Central and Southeastern United States (CSUS) only recently began applying seismic retrofit strategies for vulnerable bridges. Several states, including Illinois, Missouri, and Tennessee have begun using isolation bearings and/or restrainer cables to improve the seismic resistance of typical bridges[1]. While the effects of these retrofits are well understood for bridges in California, it is not clear how effective these retrofit measures would be for the types of bridges typically found in the CSUS. Therefore, four retrofit measures, focusing on the superstructure will be assessed to better understand their effect on modifying the seismic response of the typical bridges. The retrofit measures include: (1) replacing steel fixed and expansion bearings with elastomeric bearings, (2) replacing steel fixed and expansion bearings with lead-rubber bearings, (3) using steel cable restrainers to provide a tie from the bridge superstructure to the piers, and (4) using a combination of elastomeric bearings and steel cable restrainers. These retrofit measures, which focus on the superstructure, are chosen because they are generally less expensive and easier to perform compared with retrofits for the columns and/or foundations.

As shown in the analysis of Ref. [1], steel bearings generally have poor performance during earthquakes, since they lack the strength or deformation capacity required during an earthquake. In addition, the steel bearings may transfer undesirable forces from the superstructure to the columns. Elastomeric bearings are relatively flexible, have a much larger deformation capacity compared with steel bearings and can function to isolate the superstructure. Lead-rubber bearings, which modify conventional elastomeric bearings by inserting a lead-plug in its center, have the same isolation effects as elastomeric bearings, but also provide the added benefit of energy dissipation.

Restrainer cables are intended to limit the relative movement at expansion joints and prevent the loss of support during an earthquake. Restrainer cable retrofits became popular following the 1971 San Fernando earthquake in which many highway bridges collapsed due to excessive longitudinal movements at the expansion joints and supports[3]. Approximately 1400 bridges were retrofitted with Cable restrainers as part of a comprehensive Caltrans retrofit program[4]. The characteristics and effectiveness of restrainer cables used in typical California box-girder bridges is fairly well known through several experimental and analytical studies[5-7]. In addition, post-earthquake reconnaissance following the 1989 Loma Prieta and 1994 Northridge earthquakes showed that restrainer cables generally performed well[8], [9]. The performance characteristics of typical restrainer cables used in the CSUS are generally less well understood. However, a recent studied showed that the connection elements in the restrainer assemblies used to connect restrainers to the steel girders are considerably under-designed[10].

In this paper, experimental and analytical studies are performed to assess the performance of steel bridges that retrofitted with elastomeric bearings, lead-rubber bearings, or restrainer cables. First, the results of experimental test of the elastomeric bearings is summarized. Next, using analytical models of typical MSSS and MSC steel bridges, the effect of various retrofit strategies is assessed. Finally, recommendations for retrofit of MSSS and MSC steel-girder bridges are made.

2. EXPERIMENTAL TESTS OF ELASTOMERIC BEARINGS

2.1 Test Setup

The first phase of this study involved a series of tests of elastomeric bearings commonly used in the Central and Southeastern United States. A full-scale model of a section of a typical steel girder bridge is constructed to evaluated the characteristics of bearings, as shown in Fig. 1.

The full-scale bridge model was based on an existing steel girder bridge in Tennessee which has been considered for retrofit. The bridge superstructure was represented by two A36 W30×292 steel girders spanning 12.2 m at a distance of approximately 2.4 m on center. Three transverse stiffener beams (W30×124) were spaced between the main girders such that the loading of the bridge will remain in-plane and thus minimizing torsional effects. The dead weight of the bridge deck was represented by casting a large concrete block between the main girders. The concrete block also provided a bearing surface to which loading from the actuator can be transmitted. The superstructure of the bridge was connected to the elastomeric bearing pads, which were connected to the concrete pedestal cast on the pier caps.

The loading of the bridge model was achieved through the use of an MTS 243.45T actuator powered by a 150 pgm hydraulic power supply and dual 60 pgm servovalves. This loading system was designed to achieve a maximum speed of 200 mm/sec, with maximum forces of 440 kN in tension and 670 kN in compression.

The elastomeric bearing assembly, shown in Fig. 2, consisted of an elastomeric pad vulcanized to two steel bearing plates. The pad was 305 mm wide × 457 mm long × 129 mm high with six 4.7 mm steel laminates vulcanized to seven 14.3mm layers of rubber. The top bearing plate was 330 mm wide × 483 mm long × 38 mm thick. Four threaded holes accommodating 25 mm diameter threaded studs were made. The bottom bearing plate was 457 mm wide × 610 mm long × 25 mm

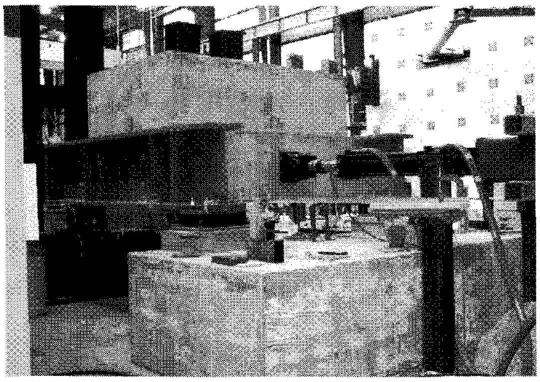


Fig. 1 Experimental Setup of Multi-Span Simply Supported Bridge Used to Tests Elastomeric Bearings

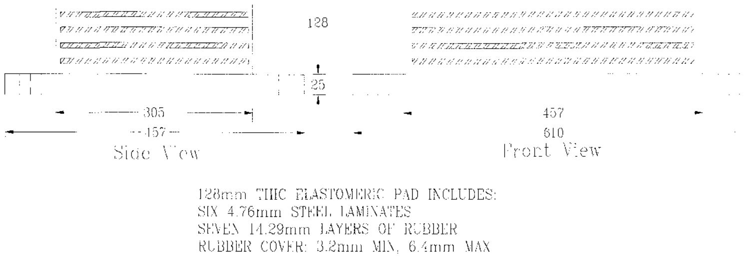


Fig. 2 Elastomeric Bearing Configuration Tested in Experimental Study

thick. Four 38 mm diameter holes were drilled in the plate to accommodate 25 mm diameter threaded studs epoxied to the concrete pedestal. Current designs in parts of the CSUS specify that the top plates are bolted to the girders and bottom bearing plates are bolted to the pier cap to avoid "walking out"underneath the girders and causing collapse of the superstructure during a seismic event.

One of the most common retrofit measures is to replace steel rocker bearings with elastomeric bearing assemblies. In most cases, the elastomeric bearings are much smaller in height than the steel rocker bearings. To accommodate the height difference, a concrete pedestal is constructed. In this study, a concrete pedestal, shown in Fig. 3, was constructed according to typical retrofit plans.

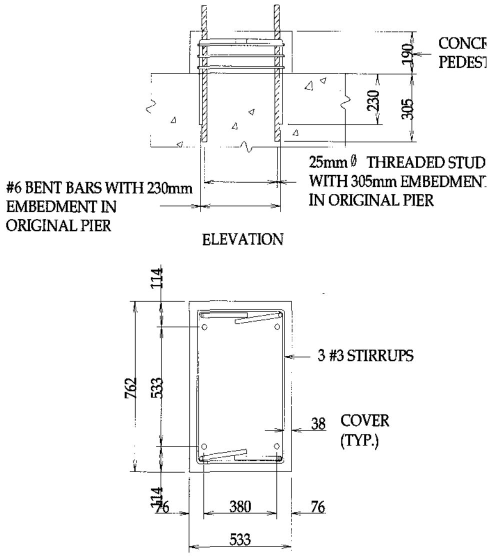


Fig. 3 Concrete Pedestal Used to Support Elastomeric Bearings

2.2 Results of Elastomeric Bearing Tests

The full-scale bridge model with elastomeric bearings, shown in Fig. 1, was tested statically and dynamically to determine the characteristics of the elastomeric bearings and the bearing/pedestal connectivity. The bridge was tested under fully reversed loading cycles at varying displacements (12.7 mm and 50.8 mm) and frequencies (0.125 Hz and 2.0 Hz). Fig. 4 shows the shear stress-shear strain plot for the bearings tested at two different frequencies: 0.125 Hz and 0.50 Hz, at a maximum shear strain of 55%.

Comparing these plots, it is observed that the characteristics of the bearings are insensitive to loading frequency. Both the effective stiffness, Keff, and the equivalent viscous damping, ξeq, are nearly identical for the two cases. Similar results were observed for the entire frequency range. It should be noted that at the higher frequencies, the

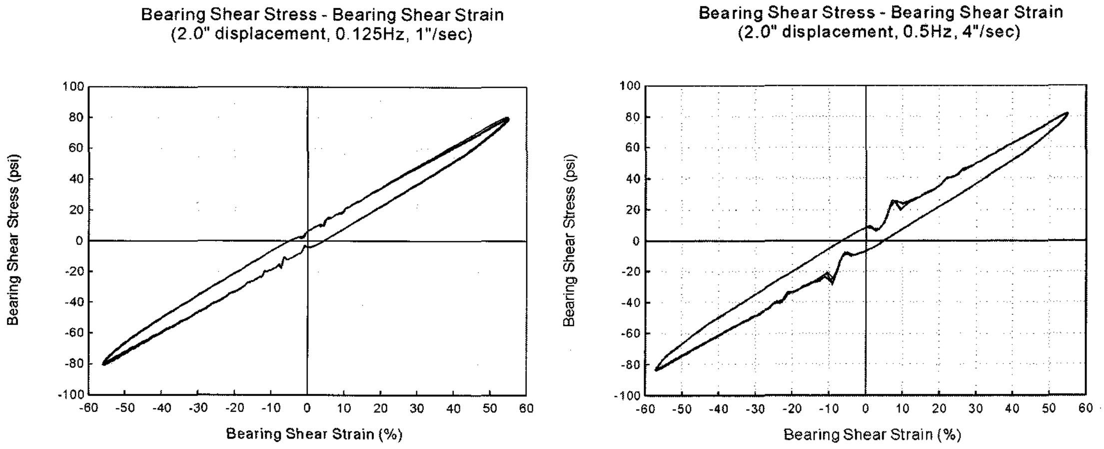


Fig. 4 Experimental Tests of Elastomeric Bearing Showing Shear Stress-Shear Strain Response at 0.125Hz and 0.50 Hz

inability of the accelerometers to produce accurate readings during the loading phase resulted in the behavior observed in reloading in the positive and negative directions.

Finally, the elastomeric bearings were tested to 100% shear strain under quasi-static loading to determine the capacity of the bearings. Upon loading to 100% shear strain, cracks began to form on the reinforced concrete pedestals. The cracks formed at the anchor bolts and continued to the top pier, as shown in Fig. 5. The 25.4 mm diameter bolts used to secure the bottom of the bearing to the pedestal yielded during the test and the concrete cracked around the bolts. Since these pedestals were designed and constructed according to existing plans used for bridges in the field, the tests confirmed the need to perform modifications to improve the performance of the pedestal. Detailed information on the results of this test can be obtained at from the research report by Choi[1].

3. ANALYTICAL MODELING OF MSSS AND MSC STEEL BRIDGES AND RETROFIT MEASURES

3.1 Analytical Modeling of MSSS and MSC S Steel Bridges

Since the multi-span simply supported and multi-span continuous steel bridges consist of elements that may exhibit highly nonlinear behavior (steel bearing, columns, abutments, impact), a two-dimensional nonlinear analytical model of the bridges is developed using DRAIN-2DX[11], as shown in Fig. 6.

Since the superstructure is expected to remain linear under longitudinal earthquake motion, it is modeled using a linear element that represents the stiffness and mass properties of the composite

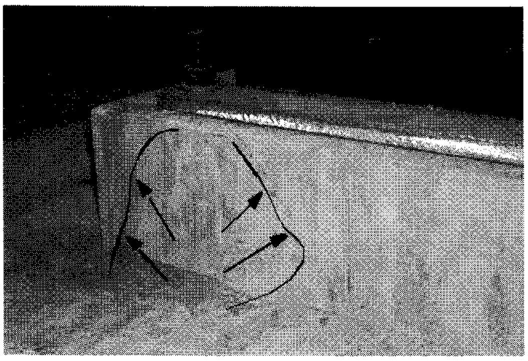


Fig. 5 Pedestal Crack Forming at 100% Shear Strain in Elastomeric Bearing

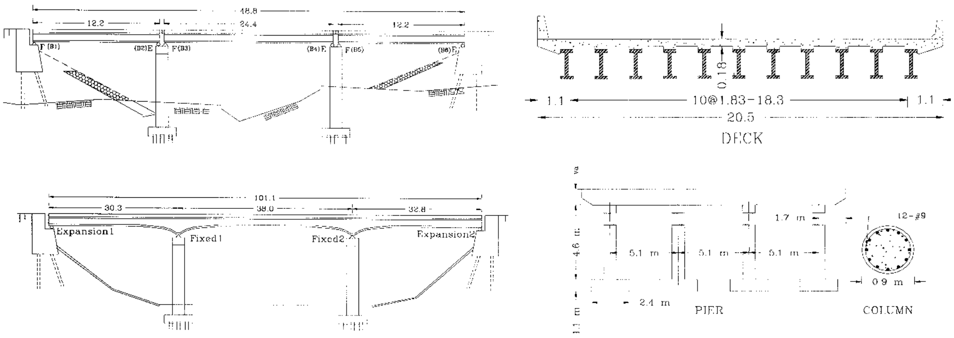


Fig. 6 Typical Multi-Span Simply Supported and Multi-Span Continuous Steel Bridge in the Central and Southeastern United States

steel girder reinforced concrete deck. The columns are modeled using the DRAIN-2DX fiber element. Each fiber has a stress-strain relationship, which can be specified to represent unconfined concrete, confined concrete, and longitudinal steel reinforcement. The distribution of inelastic deformation and forces is sampled by specifying cross section slices along the length of the element. Degradation and softening after yielding, pinching and bond slip are not included in the present model, and shear is represented elastically.

Both the MSSS and MSC steel bridge have steel rocker and fixed bearings. Experimental tests of steel bearings similar to those in the MSSS and MSC bridges in this study were conducted by Mander *et al.*[12] and Barker *et al.*[13]. The results from these tests were used to develop analytical steel bearing elements. The abutment properties used in this model are based on recommendations by Caltrans[14], and results from previous experimental studies[15], [16]. The model represents the multilinear inelastic behavior of the abutments in both active action (tension) and passive action (compression).

The contact element approach is utilized to model impact between decks and at the abutments[17]. Previous studies have shown that when a linear element with very high stiffness is used for impact, it can produce unrealistically high impact forces and accelerations[6]. Therefore, a trilinear element with elastic loading/unloading with a gap is used to represent impact between decks and deck and abutments. The pile foundation is modeled using a combination of linear springs in the horizontal and rotational directions. The pile foundation stiffness is based on the type & number of piles, as well as the soil properties.

3.2 Analytical Modeling of Retrofit Measures

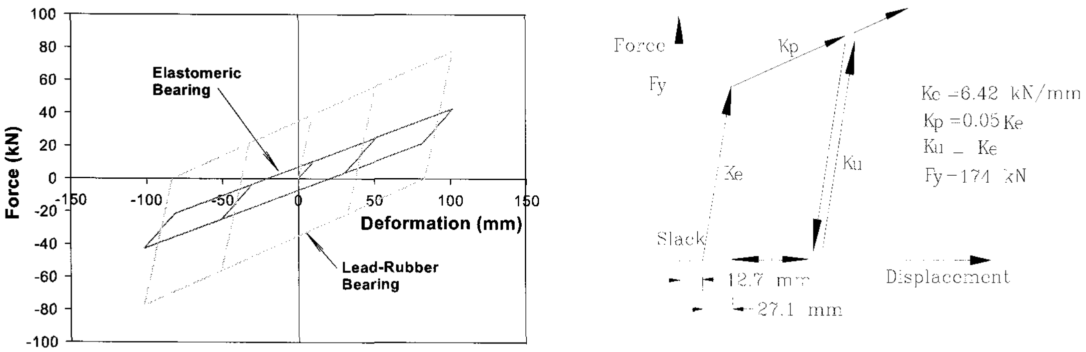
To assess the performance of the retrofitted MSSS and MSC steel girder bridges, the analytical model developed is modified to include elements for the elastomeric bearings, the lead-rubber bearings, and the restrainer cables.

The elastomeric bearings can be modeled with a bilinear element based on three parameters, K_1, K_2, and Q in Fig. 7(a)[19]. The parameters, such as elastic and plastic stiffness (K_1 and K_2) and characteristic value of an elastomeric bearing (Q), are a function of the bearing type and size. For the bearings used in this study, K_1=1.05 kN/mm and K_2 = 0.35 kN/mm are for the MSSS steel bridge, and K_1=1.58 kN/mm and K_2 = 0.53 kN/mm are for the MSC steel bridge. The values of Q are 7.1 kN and 16.0 kN, and the yield deformations of the elastomeric bearings are 10.2 mm and 15.2 mm for the MSSS and the MSC bridge, respectively.

The lead-rubber bearings having a lead-plug of 65.3 mm diameter are also modeled with bilinear following the suggestion of Skinner *et al.*[19]. The initial stiffness, K_1, is 4.21 kN/mm and the plastic stiffness, K_2, is 0.42 kN/mm forthe both type of bridges. The yield deformation of the lead-rubber bearing is 10.2 mm.

In this study, restrainers are modeled at tension-only nonlinear elements with a gap. The stiffness for the restrainer cables is based on the specified cross-sectional area of the cables, modulus of elasticity of 69000 MPa, 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 stiffness of a restrainer-cable is 6.42 kN/mm with a slack of 12.7 mm, which is installed at the end of each girder. The analytical modelings of the three retrofit measures are shown in Fig. 7.

The seismic response analysis is performed for the bridges subjected to the suite of ground motion for the 2% PE in 50 years ground motion



(a) Elastomeric/Lead-Core Bearings (b) Restrainer Cables

Fig. 7 Analytical Models Used for Elastomeric Bearings, Lead-Core Bearings, and Restrainer Cables

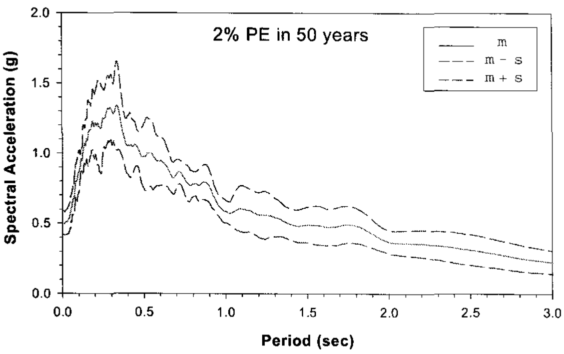


Fig. 8 Mean Acceleration Response Spectra for 2% Probability of Exceedance Ground Motion Records for Carbondale, IL

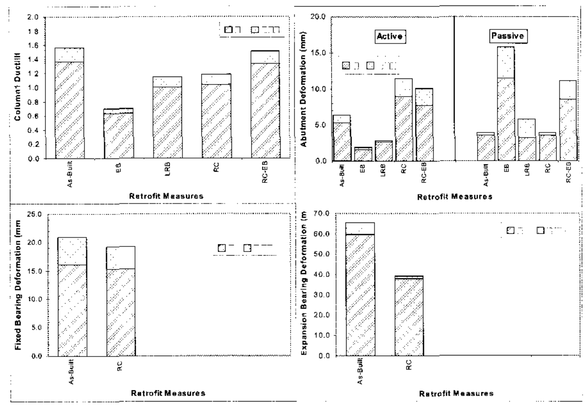


Fig. 9 Mean and Mean Plus One Standard Deviation of the Seismic Response Parameters for the MSSS Steel Bridge Using Elastomeric Bearings, Lead-Rubber Bearings, Restrainer Cables, and Restrainer Cables with Elastomeric Bearings

suite for Carbondale, IL. The mean +/- 1 standard deviation of the response spectra for the ground motion suites are shown in Fig. 8.

4. SEISMIC RESPONSE OF RETROFITTED MSSS STEEL BRIDGE

Fig. 9 shows a comparison of the mean plus one standard deviation of the column ductility, abutment deformations, fixed bearing deformation, and expansion bearing deformation for the four retrofit measures discussed above. The seismic analysis of the as-built bridges, showed that these parameters were critical in the seismic response of the MSSS and MSC bridges[1]. The comparisons for the column 1 ductility, shown in Fig. 9, show that the elastomeric bearings are effective in reducing the ductility demands on the column. The mean-plus-one standard deviation of the ductility demand for the bridge retrofitted with elastomeric bearings is approximately $\mu=0.75$, compared with $\mu=1.58$ for the as-built bridge. Elastomeric bearings, however, have mixed results at the abutments. In active action, elastomeric bearings result in smaller deformations at the abutments, compared with the as-built case. However, in passive action, the elastomeric bearings result in significant demands on the abutments, due to pounding between the deck and the abutment.

The results with lead-rubber bearings are similar to those with elastomeric bearings. The mean-plus-one standard deviation of the column ductility demand with the lead-rubber bearings is approximately μ=1.15 a 27% reduction from the as-built case. The lead-rubber bearings are slightly less effective in reducing the column ductilities than the elastomeric bearings because the lead-rubber bearings have a higher effective stiffness. However, the lead-rubber bearings lead to a reduction in deck displacements, which result in smaller demands on the abutments compared with the elastomeric bearings.

Restrainer cables are typically used to limit relative hinge opening at the joints and/or to prevent collapse due to unseating. In some cases, restrainer cables are used with the existing steel fixed and rocker bearings. In such cases, restrainers are expected to limit the displacement of the rocker bearings (thus preventing toppling), or to prevent unseating should the fixed bearings fail. The column ductility demands with restrainer cables is 25% less than the as-built bridge. The restrainer cables are not very effective in limiting the steel fixed bearings, since the controlling deformation levels are much smaller than the slack in the cables. The restrainer cables are moderately effective in limiting the deformation of the steel rocker bearing. The rocker bearing deformation was reduced from a mean-plus-one standard deviation of 65 mm in the as-built bridge to a mean-plus-one standard deviation of 39 mm with restrainer cables. The restrainer cables, had mixed effectiveness at the abutments. In passive action, the restrainers had no effect. This is expected, since the cables act only in tension. In active action, the restrainer forces at the abutment led to increased abutment deformations, compared to the as-built case.

Restrainer cable retrofits are often accompanied by replacing of steel bearings with elastomeric bearings. In these cases, the bearings are used to isolate the superstructure and to eliminate the highly vulnerable steel bearings. The restrainers are used to limit the hinge displacement and act as a fail-safe for unseating. The results show that when restrainer cables are used with elastomeric bearings, the mean-plus-one standard deviation of the column ductilities increases significantly compared with the case with elastomeric bearings only. The column demand with the restrainer cables and elastomeric bearings are approximately the same as the as-built response. Elastomeric bearing increase the deck displacement by adding a flexible layer between the deck and pier. Analysis shows that this results in reduced demands on the columns. However, when restrainer cables are used with the elastomeric bearings, the effect of isolation is negated since the restrainers provide a mechanism to transfer force from the deck to the column.

5. SEISMIC RESPONSE OF RETROFITTED MSC STEEL BRIDGE

Fig. 10 shows a comparison of the column ductility, abutment deformations, fixed bearing deformation, and expansion bearing deformation for the MSC bridge in the as-built condition compared to the four retrofit strategies described above. One of the major deficiencies in the as-built MSC bridge is the ductility demands on the column. Replacing the steel fixed bearings with elastomeric bearings has a significant effect on the mean-plus-one standard deviation of the column ductility demands. The column ductility demands decrease from a mean-plus-one standard deviation of μ=2.52 in the as-built case to μ=0.60 with elastomeric bearings. However, the abutment deformation in passive action is significantly increased due to the increased deck displacements.

Lead-rubber bearings used at the piers and abutments are also evaluated. The results show that the lead-rubber bearings reduce the column ductility demands from mean-plus-one standard deviation of μ=2.52 in the as-built case to μ=0.80. The lead-rubber bearings improve the abutment behavior in passive action, while only moderately increasing the abutment deformation in active action.

The effect of restrainer cable retrofit is evaluated in the MSCbridge by placing restrainer cables at the abutments and at the piers. The goal of the cable restrainers at the abutments would be to limit hinge opening, rocker bearing deformation, and to prevent collapse due to unseating. The restrainer cables at the piers would be used primarily to limit displacement at piers if the fixed steel bearings fail. Fig. 10 shows that the restrainer cables have a negligible effect on the mean-plus-one standard deviation of column ductility demands. This is expected since the column ductility demand is controlled by the fixed bearing support. The restrainer cables slightly increase the active deformations at the abutments, while decreasing the passive deformations. The restrainer cables slightly increase the active deformation at the abutments, deformations of the fixed bearing.

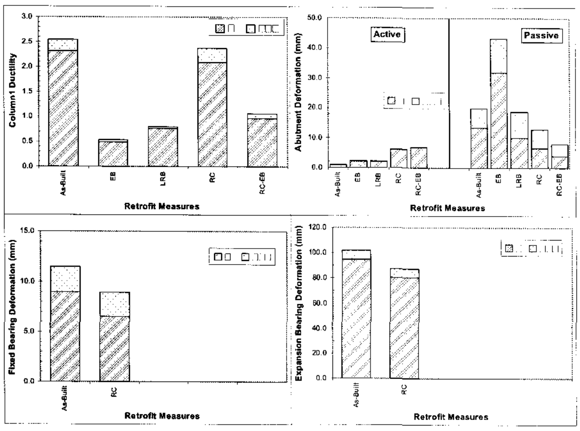


Fig. 10 Mean and Mean Plus One Standard Deviation of the Seismic Response Parameters for the MSC Steel Bridge Using Elastomeric Bearings, Lead-Rubber Bearings, Restrainer Cables, and Restrainer Cables with Elastomeric Bearings

Finally, the use of elastomeric bearings and cable restrainers in the MSC bridge are evaluated. At the columns, the use of elastomeric bearings and restrainer cables slightly reduces the column ductility from a mean-plus-one standard deviation of μ=2.52 in the as-built case to μ=2.00. However, this is considerably more than the case with elastomeric bearings only.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper evaluates the effectiveness of various seismic retrofit strategies on the seismic response of typical multi-span simply supported (MSSS) and continuous steel (MSC) girder bridges in the Central and Southeastern US (CSUS). Experimental tests of elastomeric bearings and restrainer cables are performed, and analytical models of typical bridges are developed.

The experimental tests of the elastomeric bearings found that the elastomeric bearing behavior is independent of loading frequency for a range of frequencies up to 1 hz. The concrete pedestal typically used to support the elastomeric bearings was found to be vulnerable to cracking near the anchor bolt at load levels corresponding to 100% shear strain in the bearings. Shear strain levels of 100% were obtained in cases for the MSC steel-girder bridge. This indicates that the reinforcement for the pedestals need to be improved to accommodate the forces transferred through the bearings.

Analytical studies are performed to evaluate the effectiveness of the following retrofit measures (1) replacing fixed and rocker bearings with elastomeric bearings or lead-rubber bearings, (2) restrainer cables connected from the deck to the pier, and (3) restrainer cables and elastomeric bearings. The effectiveness of the retrofit measures varied considerably. In addition, since each retrofit measure changed the seismic characteristics of the bridge, it resulted in reducing demands on one component, while increasing the demands on another.

Elastomeric bearings effectively reduced the demands on the column in the MSSS and MSC bridges by approximately 52%, and 72%, respectively. However, the elastomeric bearings increased the deck displacement resulting in large demands at the abutments compared with the as-built case.

The lead-rubber bearings had similar effects on the column demands resulting in reductions in column ductilities of 25%, and 68% for the MSSS and MSC bridges, respectively. However, the added damping provided by the lead-rubber bearings reduced the deck displacement and resulted in reduced demands on the abutments.

Restrainer cables used with the existing steel fixed and rocker bearings had mixed effects on the seismic response. The restrainer cables were effective in reducing the column ductility demands and expansion bearing deformations in the MSSS and MSC bridge. In the MSSS bridge, the column ductility demands and the expansion bearing deformations were reduced by 25% and 38%, respectively. In the MSC bridge, the restrainers were slightly less effective, reducing the column ductility demands and expansion bearing demands by 6% and 9%, respectively.

The restrainer cables did not do much to decrease the deformation demands on the fixed bearings. The results indicate that restrainer cables are generally more effective in improving the seismic performance of the MSSS bridge compared with the MSC bridge. This may be appropriate since restrainers are generally used more for the MSSS bridges.

Often, elastomeric bearing retrofits are accompanied by restrainer cables to reduce the deck displacement and prevent collapse due to unseating. In general, the combination of restrainer cables and elastomeric bearings does little to improve the seismic performance of MSSS & MSC bridges. In fact, it is observed that the restrainer cables typically negate the beneficial isolation effects obtained from elastomeric bearings.

Based on the analyses in this study, it is recommended that if restrainer cables retrofit are performed in combination with elastomeric bearings retrofits, the restrainer shouldbe provided with adequate slack to allow the elastomeric bearing to effectively isolate the bridge superstructure and limit the demands on the columns. The amount of slack required to do this depends on the characteristics of the bridge, and the intensity of the ground motion.

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