STOPPER-BEARING SYSTEM: A solution to displacement control of bridge decks

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ABSTRACT

Bridges play an important role in society, especially in the post-earthquake period that enables emergency traffic to reach isolated areas to minimize the loss of property and life. Some past earthquakes have revealed large horizontal displacements of the superstructure that resulted in unseating of bridge spans and lead to an interruption of transportation. These large displacements may also result in pounding of adjacent decks, which is another concern that introduces unexpected forces into the bridge system and may damage some other critical components such as the bearings and anchor bolts. The aforementioned vulnerabilities can be eliminated by properly limiting the horizontal displacement between the decks and piers. Therefore, a new bearing system equipped with a stopper is proposed in this study as one solution to address these concerns. The horizontal displacement of a deck can be limited to a desired range using this system. From seismic data of the Chi-Chi, Taiwan (0.79g) earthquake in the analytical computing of a prestressed concrete bridge, this new bearing system is proven to be feasible. Detailed analytical modeling of a stopper-bearing system is developed using ABAQUS software to show its performance when subjected to equivalent ground motion forces.

Keywords: Restrainers, Prestressed bridges, Unseating, Earthquakes, Displacement

INTRODUCTION

Past major earthquakes have caused not only the loss of properties and lives but also serious damage to essential living facilities. From these past experiences, the traffic system has played a key role in the post-earthquake period. A well-functioned traffic system can minimize the impact caused by the earthquakes and accelerate the rehabilitation. Bridges are critical components in the traffic system that act as links and connect separate areas. However, some bridges are vulnerable structures when a major earthquake occurs. Strong earthquakes can lead to out-of-phase motions of frames and result in impact at the expansion joint[1]. Pounding between adjacent decks causes large relative displacements between the deck and pier while introducing large lateral forces that may result in the failure of the bearings, subsequently leading to unseating of bridge decks. Unseating can also impair and even inhibit traffic flow on or beneath a bridge. Moreover, a dysfunctional, damaged bridge can interrupt rescue actions from ambulances and fire engines that transport emergency responders to help save lives and properties.

To mitigate this phenomenon, restrainers such as restrainer cables, high strength bar restrainers, bumper blocks, shear keys, keeper brackets, and steel pipe restrainers, have been used to limit the relative displacements at expansion joints to a desirable level. However, many bridges that were retrofitted by restrainer cables failed in both the 1989 Loma Prieta and 1994 Northridge earthquakes.[2] Some of these failures resulted from rupturing of the restrainers, anchorage plates being pulled through the concrete diaphragms, swaged fittings being pulled away from the cables, and anchorage nuts that seemed to loosen from the ends of cable units. Additional studies of these failures also noted that large horizontal displacements may be caused by pounding between adjacent decks, where additional lateral force is transferred to other components. Previous work conducted by Ala Saadeghvaziri and Yandani-Motlagh[3] suggest that the shear forces in the bearings due to span impact are higher than that of the capacity of the bolts. These results show that failure of the bolts may not necessarily cause bridge failure; however, the impaired bolts are potential vulnerabilities for the next major earthquake. Regular inspection and replacement of bolts may have an impact on traffic flow and may be uneconomical. In addition, the corrosion of anchor bolts due to moisture, deicing salts, and other chemical materials is also another concern. Therefore, there exists a need to develop a system that resists large forces and stress concentrations by making a connection that is reliable and resilient to limit displacements within a bridge system.

In this study, efforts are made to find a solution for displacement control to avoid unseating of a prestressed concrete bridge. The focus is on the capability of a proposed stopper-bearing system that is designed to resist lateral forces generated by ground motions in two ways: 1) bearings are free to deform, thereby dissipating energy on their own and 2) bearings will have reserved lateral capacity that can be gained through a steel stopper, which can dissipate additional energy while allowing the system to remain stable and limit unseating. An analytical model developed in ABAQUS is developed to evaluate the proposed stopper-bearing system. The results of the modeling from SAP2000 are used to validate the analytical values based on a case study of a prestressed concrete bridge having a total length of 400 ft (121.92 m). In practice, the lateral forces transferred to the columns should be evaluated to verify that the columns will not fail. Given this proposed system, constructability is an important concern and is taken into account and described in this paper. A series of steps is presented to provide a better understanding of how the system will be constructed.

PROPOSED DESIGN AND CONSTRUCTION METHODOLOGY

The purpose of this research is to reveal a new design for a stopper-bearing system that can limit unseating of bridge spans while enabling the system to dissipate energy in a displacement-controlled environment. The proposed system has the following advantages and benefits:

- **Displacement limiting system:**

A stopper, consisting of a rectangular box made of steel, encases an existing bearing that is located between the bridge superstructure and substructure to provide additional, reliable lateral shear resistance. With proper design, the displacement of the deck can be controlled in a desired range, and provide reserved lateral capacity in addition to the shear capacity of the existing bearings.

- **Bearing protecting system:**

This system allows the existing bearings to deform as designed. The bearings are protected by the stopper from excessive lateral deformation, which might result in failure of the bearings. As long as lateral displacement is properly controlled within expected ranges[4], bearings can have desirable performance through entire periods of earthquakes.

- **Unseating preventing system:**

Unseating of the decks occurs if very large relative displacements between decks and piers are introduced. When lateral displacement is well-controlled, the probability of unseating of decks will be reduced.

- **Mitigating effects from pounding:**

Generally, pounding between adjacent decks in earthquakes may introduce considerable additional forces on the bearings. It is expected that this stopper-bearing system can limit unexpected lateral displacements to avoid pounding between decks. Moreover, expected pounding between deck component and stopper can alter the load path to minimize the forces transferred to the bearings and mitigate undesired effect by pounding.

- **Advanced longitudinal shear key:**

Nowadays, concrete shear keys can be found in front of the end diaphragm to serve as the first unseating device.[5] However, insufficient space on bent cap limits the application of this efficient device on many bridges. The stopper-bearing system requires no additional space to achieve the same function and can be installed on existing bent caps. Furthermore, the proposed system with a stopper inside can prevent the deck from moving forward in all directions when there is unexpected lateral displacement.

PROPOSED DESIGN

The system consists of three parts all made of steel: 1) deck component, 2) stopper, and 3) base component (Fig. 1). While different bearings can be used, this study is solely based on elastomeric bearings for its bearing component. As such, an elastomeric bearing is fixed to the base component and deck component. The deck component is attached to the bottom of girder, and the base component is fixed to the bent cap. The size of deck component can be decided to achieve expected performance. The size of base component is designed according to the size of elastomeric bearing located in the center of the system and the width of the bent cap. The base component is fixed on the bent cap like a hat by jacking the flange part of base component to the bent cap. The required lateral resistance is derived when the flange pushes the bent cap from the side. The stopper is designed such that it is able to resist large horizontal forces when subjected to strong ground motions. The dimensions of the stopper are based on the size of the existing bearing, the predicted lateral force under earthquake, and the allowed horizontal displacement. In this paper, a 26-inch-wide steel, square stopper is studied and presented. The thickness of each web is 2 inches (5 cm). The stopper fits into a steel base component and can be replaced easily if needed. A detailed sketch is shown in Fig. 2, and a three dimensional sketch of base component, stopper, and elastomeric bearing is shown in Fig.3.

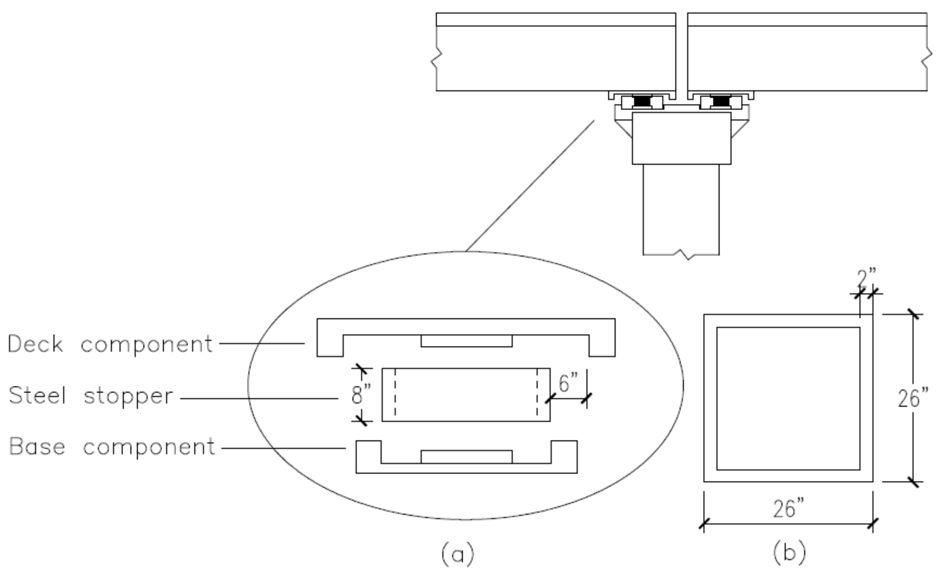

Fig. 1 (a) Side view of deck component, stopper, and base component, (b) top view of stopper

When an earthquake takes place, the deck initially has a small displacement and the stopper does not interrupt the movement of the deck since such displacement does not reach the designed limitation. In this condition, the bearing is the only component that works and dissipates energy. As the ground motion is amplified, the relative deck displacement reaches the design limit, and the deck component contacts the stopper. From this contact, movement of the deck is prevented and the force is transferred to the column through an altered load path via the stopper-bearing system. In other words, the system transfers load to the columns in a similar manner in which restrainers transfer loads. However, it is expected that the altered load path to the stopper-bearing system will dissipate more energy within the system, thereby minimizing the forces that could be potentially transferred to the columns. Further investigations are being conducted to evaluate and quantify this phenomenon on bridges designed with the proposed stopper-bearing system given a specific demand.

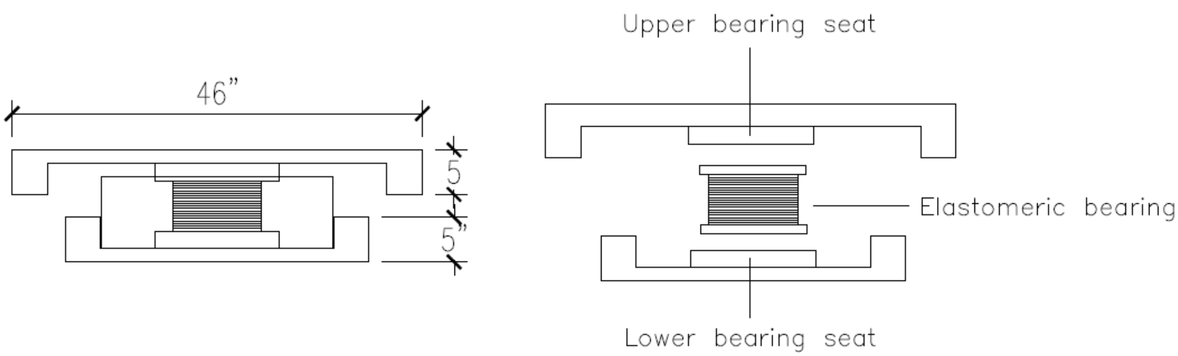

Fig. 2 Layout of the stopper bearing system

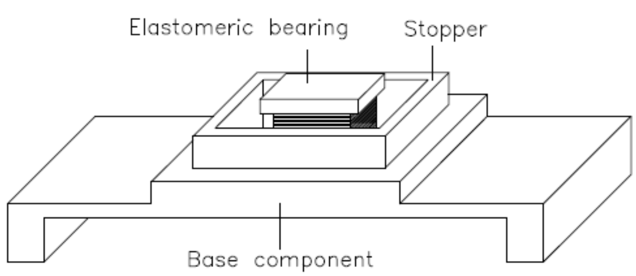

Fig. 3 Base component, stopper, and elastomeric bearing

CONSTRUCTION METHODOLOGY

The construction process is an important issue in practice. This device can either be applied as new construction or retrofit tactic, where the construction processes are similar. To install this device, there are four components that should be assembled properly as shown in Fig. 4. First, the size of base component is decided upon based on the size of the elastomeric bearing and the width of bent cap. This component can easily fit onto a bent cap through bolted connections. However, these bolts are designed to resist tensile forces not shear. The horizontal force is carried by the flanges of the base component. Once the base component is in tact, the elastomeric bearing fits into a slot on the bearing seat of base component and is positioned or “fixed” into place by bolts that will act in tension. The stopper is then placed into the base component and the bearing is centered on the base component. In the opposite face of elastomeric bearing, the upper bearing seat is attached with bolts fastened from the top. Finally, the girders can be placed on deck component and the bolts can be connected.

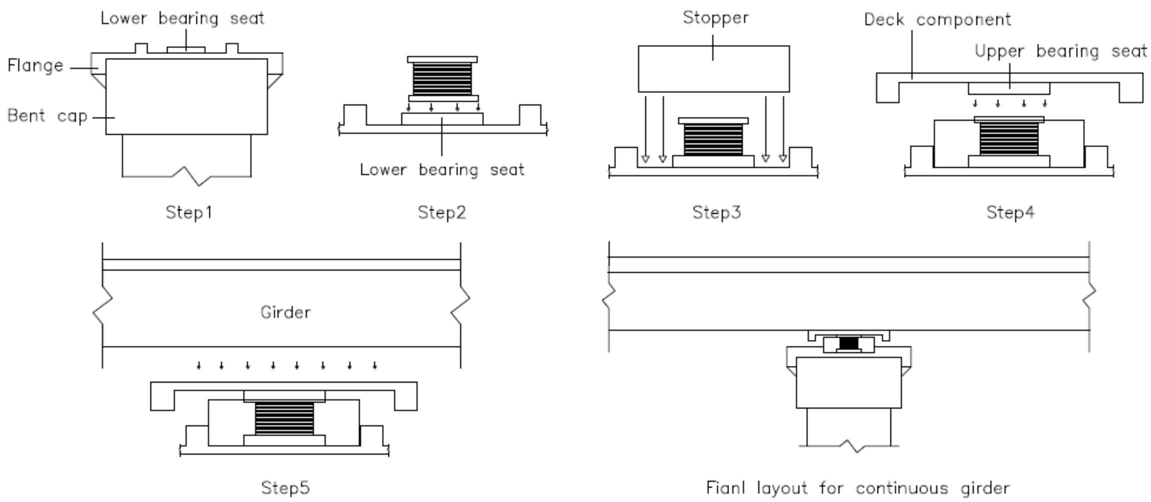

Fig. 4 Procedure of construction

ANALYTICAL BRIDGE MODEL – SAP2000

In this paper, two case studies are studied and performed on a prestressed concrete bridge with prestressed T-beams for a 2-span and 8-span bridge. The model created by SAP2000 has a 50 ft (15.24 m) long span with six prestressed concrete T-beams. The width of the deck is 42 ft (12.8 m), and the height of the girders is 4 ft (1.2 m) supporting a 1-foot-thick slab. All tendons are prestressed with a force of 100 kips. The seismic data of Altadena, Lucerne, and Chi-Chi earthquake are introduced in the model to determine the structural response of the bridge via a nonlinear time history analysis conducted in SAP2000. From the analyses of these three earthquakes, the maximum lateral reaction force in one bearing is 618.91 kips (2752.9 kN), which resulted from the 1999 Chi-Chi earthquake. This force serves as the preliminary upper bound design force for the stopper system and is used to verify the model constructed in ABAQUS. The reaction forces at the abutment are extracted and conservatively used to predict the expected forces that would be transferred to the bearings. These results are listed in Table 1.

Table1 Maximum lateral force at abutments when subjected to ground motions

No. of bridge spans in prestressed bridge model	Recorded earthquake ground motions used in analysis		
	Altadena (0.45g)	*Lucerne (0.65g)*	*Chi-Chi (0.79g)*
2	107.72 kips (479.1 kN)	194 kips (862.9 kN)	260 kips (1156.5 kN)
8	424.24 kips (1887 kN)	486 kips (2161.7 kN)	618.91 kips (2752.9 kN)

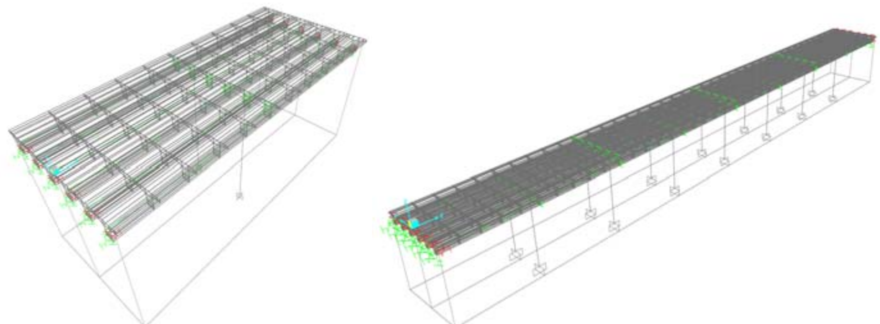

Fig. 5 SAP2000 bridge model for 2-span and 8-span prestressed bridge, respectively

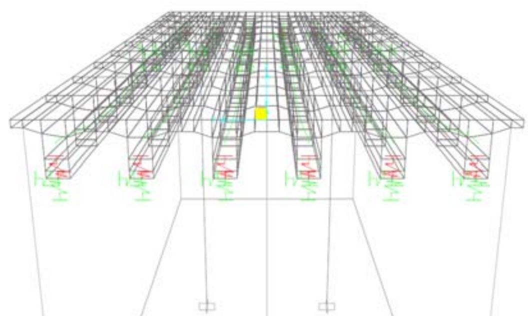

Fig. 6 Cross-section of bridge girders

ABAQUS MODEL

A 26-inch-wide stopper model is constructed in ABAQUS, having a finite element mesh size of 0.5 cm. Since the focus is on the behavior of the stopper, the deck component is analytically modeled with a rigid element. A lateral force is applied on the rigid element as the forcing function that moves the stopper. Then, the applied force is transferred to the stopper when the two parts contact. The stopper fits into a pocket of the base component, therefore, the base component is also modeled to simulate the real situation. The lateral force, 618.91 kips (2752.9 kN), is taken from the result of 1999 Chi-Chi earthquake on a bridge with eight spans. Several lager forces are also applied in order to find the limits of the stopper.

RESULT AND ANALYSIS

The results of the modeling show that the capacity of the stopper is not exceeded even when subjected to a large lateral load of 618.91 kips (2752.9 kN). In fact, the stopper still remains elastic under this magnitude of force, having a maximum stress of 54.2 ksi (373.7 MPa), which is a stress concentration that occurs at the contact surface of these two parts. Note, high strength steel is used in this design, where the yield stress is 55 ksi (380 MPa). At the central part of the stopper, the stress is in the elastic range, which indicates that this stopper having two 2-inch-thick webs is safe and reliable under this designed load. The deformation of the stopper in the direction of the force is 0.11 inches (0.0028 m), which is relatively small and does not affect the expected performance of the stopper system. Fig. 7 shows the critical parts of the stopper that are in contact with the rigid surface when the two components touch when modeled in ABAQUS. This geometric discontinuity leads to relatively high stress concentrations compared to the stress in the web of the stopper. In Fig. 8, the result of additional modeling shows that for this stopper subjected to a force of 900 kips (4003.2 kN), the stopper yields upon contact and a visible deformation takes place. This extreme condition gives an idea of the failure mechanism. Although yielding decreases the capacity of the stopper and leads to large plastic deformations, a significant amount of energy is dissipated. Fig. 9 shows the force-deformation relationship and corresponding energy dissipation through the plastic behavior of the stopper in a deformation range of 5 cm (2 inches). Therefore, the deformation of stopper should be taken into account to make sure that the expected function and performance of the system under ground motion will not be interrupted. In other words, the elastomeric bearing should be able to deform within an expected range and the deck movement is still controlled in a preferable range after the stopper deforms locally. The design force should be considered when the stopper begins to yield, and the capacity and resistance provided by the column should also be assessed. The stopper will be designed to yield before the transferred lateral force exceeds the capability of the column. Ultimately, the stopper-bearing system serves as the second energy dissipater to minimize the additional forces that may be transferred the columns.

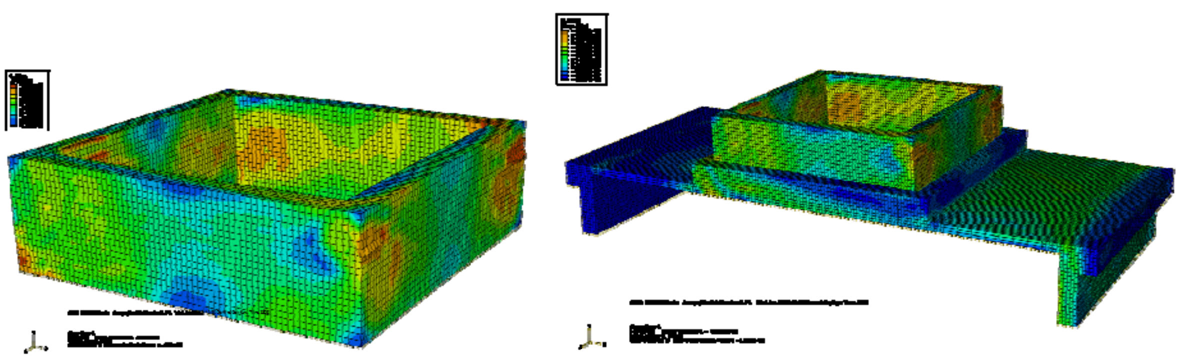

Fig. 7 Stress contour for stopper and base component subjected to lateral force of 618.91 kips (2752.9 kN) with a maximum stress of 54.2 ksi (373.7 MPa) shown in red

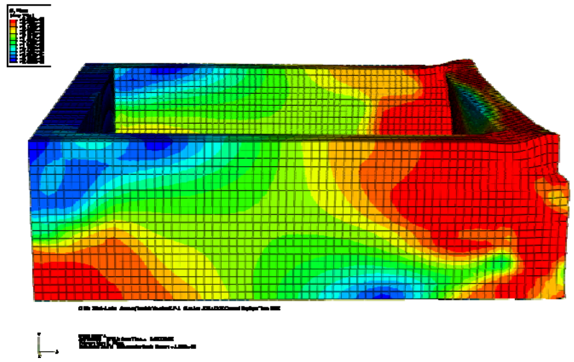

Fig. 8 Stress contour and local yielding for stopper under 900 kips (4003.2 kN) lateral force with maximum stress of 55 ksi (380 MPa) shown in red

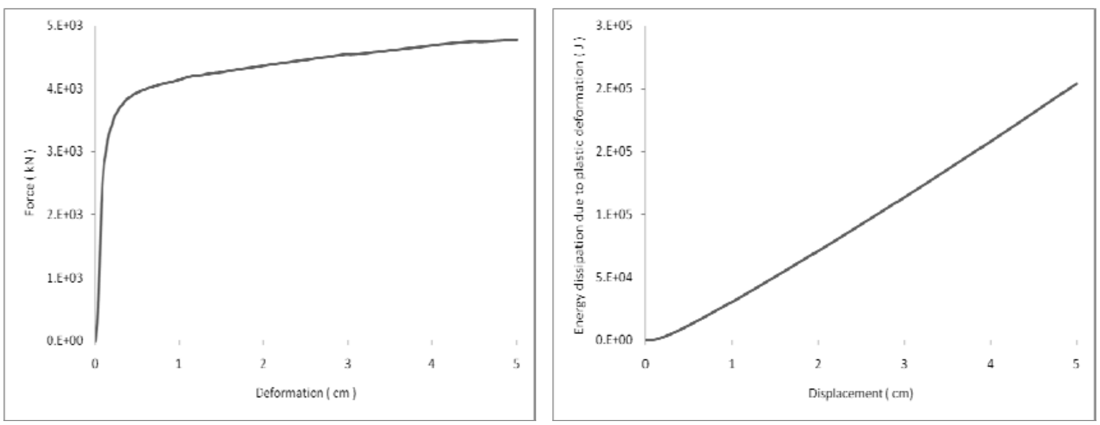

Fig. 9 Force-deformation relationship and plastic dissipation for the stopper with two 2-inch-thick webs in a deformation range of 5 cm (2 inches)

CONCLUSIONS

In this paper, the capacity of the stopper is shown through an analytical model that is developed using ABAQUS. The results show the stresses and deformations to be acceptable, where the benefits of the proposed design are apparent. In addition, the movement of the deck can be limited in a preferable range. In this case, relative displacement between girders and bent cap is limited in a range of 6 inches (15.24 cm) in both longitudinal and transverse directions given the newly proposed stopper-bearing system that is presented and described herein. The deformation of stopper is 0.11 inches (0.28 cm), which can be considered to be negligible. In practice, various preferable ranges can be achieved by adjusting corresponding dimensions of the deck component, which adds to the versatility, efficacy, reliability, and benefit of this design. By selecting adequate thickness of the webs, energy can be dissipated through local yielding of the stopper under expected lateral load. With careful design, the stopper-bearing system can serve as an effective stopper and an energy dissipater simultaneously. Another advantage of the stopper-bearing system is that it is able to limit the movement in both the longitudinal and transverse directions at the same time, thereby combining the functions of a longitudinal restrainer and a transverse restrainer. However, as the excessive displacement of deck is prohibited by this system, additional lateral force will be transferred to the column as well. The need of additional retrofit work to the substructure should be taken into account to maintain the integrity of the whole bridge system.

FUTURE STUDIES

The stopper-bearing system will be fully integrated into a bridge model to capture its performance and study how this device affects the behavior of the bridge response when subjected to various ground motions. Emphasis will be placed on assessing the effects of the columns when subjected to additional lateral load transferred through this system. Another focus will be the installation of the deck component and base component. Both these two parts should be fixed firmly to the girder and bent cap in order not to have unexpected slip. The ability of the stopper to dissipate energy through local yielding will be studied and the results will serve as a reference for determining the web thickness of the stopper. . A prototype model will need to be constructed and experimentally tested to validate the analysis conducted herein.

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