STOPPER-BEARING SYSTEM – A SOLUTION TO DISPLACEMENT CONTROL OF BRIDGE DECKS

A Thesis

by

YI-TE TSAI

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

MASTER OF SCIENCE

August 2009

Major Subject: Civil Engineering

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Approved by:

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ABSTRACT

Stopper-Bearing System – A Solution to Displacement Control of Bridge Decks.

(August 2009)

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Chair of Advisory Committee: Dr. Monique Hite Head

Bridges play an important role in society, especially during the post-earthquake period that enables emergency vehicles and traffic for safe egress and ingress to minimize the loss of property and life. However, some past earthquakes have resulted in large horizontal displacements on the superstructure that have lead to unseating of bridge spans and unexpected pounding forces that damaged critical components such as bearings and anchor bolts. To this end, a new bearing system, referred to as a stopper-bearing system (SBS), is proposed as one solution to address the vulnerability of bridge bearings and other components. The horizontal displacement of a deck can be limited to a desired range using the SBS. The nonlinear load-deformation behavior of the SBS is obtained from ABAQUS and used to define the SBS within reinforced concrete analytical bridge models developed in SAP2000, which are subjected to the 1999 Chi-Chi, Taiwan earthquake ground motion (1.01g – E-W component and 0.43g – N-S component). The results from the nonlinear time history analyses show that the SBS is effective in limiting bridge deck displacements and pounding effects. Preliminary

analytical modeling of the SBS shows promise as a solution to displacement control of bridge decks for overall enhancement of bridge performance during seismic events.

DEDICATION

Dedicated to my family

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Finally, thanks to my father, mother, and sisters for their encouragement and to my wife for her patience and love.

NOMENCLATURE

G	Designed gap width between deck component and stopper
g	Gap between deck component and stopper during ground motion
N-S	North – south direction
E-W	East – west direction
PGA	Peak ground acceleration
SBS	Stopper-bearing system

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1. INTRODUCTION

1.1 Introduction

Past major earthquakes have resulted in not only the loss of properties and lives but also serious damage to essential living facilities. From these experiences, the traffic system plays a key role in the post-earthquake period since they act as links in the transportation network. A well-functioned traffic system can minimize the damage caused by the earthquakes and need for repair. However, some bridges are vulnerable when a major earthquake occurs, particularly its bearings and other substructure components [1].

Previous work suggests that the shear forces in the bearings due to pounding of decks are several times higher than the capacity of the bolts [2]. The results show that failure of the bolts will not necessarily cause large displacement of the deck; however, the impaired bolts are potential vulnerabilities when the next major earthquake comes. Regular inspection and replacement of bolts may result in impact to the traffic flow and be uneconomic.

Bearings dissipate energy through the hysteretic behavior, however, under certain horizontal displacement will result in shear failure and further lose the ability to dissipate earthquake energy [3]. Therefore, the horizontal displacement of the bearings should be kept in a safe range to ensure expected performance.

This thesis follows the style of Engineering Structures.

Although pounding causes some potential threats to bridge structures, there are some advantages that can be provided by pounding as well. Some researchers have suggested that pounding generally reduces the response of bridge frames because of the energy dissipated during pounding and because pounding disrupts the buildup of resonance [4]. It is important for this research to obtain the advantages from the pounding effect and minimize the disadvantages it causes.

Large deck displacements caused by strong earthquakes can result in pounding between adjacent decks and introduces additional lateral force into the components. Past severe earthquakes indicate that pounding may cause considerable damage or even lead to collapse of structures [4]. For simply supported bridges, unseating can be defined as collapse of a bridge deck. The damaged bridge will therefore hinder egress and ingress of most rescue vehicles, like ambulances and fire engines, and more time would then be required to save lives and properties. Moreover, unseating can also result in danger to the traffic flow traveling through or beneath the falling bridge span. Therefore, there is a need to help minimize large deck displacements and unseating of bridge decks to maintain function their even after major earthquakes.

To address this need, a stopper–bearing system has been designed and analytically calibrated as a solution to control displacement of bridge decks. So when an earthquake occurs, pounding may exist in the stopper bearing system if deck movement exceeds designed values. This pounding force will be transferred to substructure mainly through SBS since it has much larger rigidity than bearings. It is important that the additional force transferred plus existing lateral force will not result in failures of columns. Therefore, the capacity of columns is a key factor for selecting an appropriate SBS, which can be customized to reduce the effect of additional force transferred to the columns. An ideal situation is to keep both the deck displacement and the force in column in safe level under earthquakes. While the two expectations may be seemingly contradictory, the effectiveness of SBS depends on lateral resistance it can provide, and balancing acts can be made to find a solution to effectively control deck displacement and maintain integrity of bridges.

1.2 Objectives

In order to eliminate the above potential threats, research is conducted for the development of a stopper-bearing system to achieve the following advantages and objectives:

1. Bidirectional deck displacement limiting system: There is a stopper that sits between the deck and base components that provides reliable lateral shear resistance. With proper design, the displacement of girders can be controlled in a desired range. Once lateral displacement is properly controlled, bearings can also be protected and have expected performance through entire periods of major earthquakes. In addition, the probability of the unseating of decks will be reduced as well. Pounding between adjacent decks is another threat to the bridge. Careful design of this system can reduce unexpected lateral displacement and eliminate the possibility of pounding between two decks. Pounding will still occur when the gap between deck component and stopper closes. However, the pounding force will be

transferred to the substructure mainly through the SBS rather than bridge bearings, while SBS will help to dissipate some of the energy.

2. Control resultant force transferred to substructure when limiting deck movement: When the stopper-bearing system stops the deck from moving, corresponding resisting force is transferred to substructure. The stopper of this system can be adjusted by applying various stiffeners to possess different lateral resistance and meet various expected performance according to capacity of the column bents and desired deck displacement. In addition, gaps between the stopper and deck component can also be adjusted to yield different performance. Therefore, the amount of force transferred to columns and abutments can be maintained in a safe range.
3. Energy dissipating system: When pounding occur between deck component and stopper, plastic deformation will happen in the stopper, and energy will be dissipated as a result of the pounding. The energy dissipated mainly depends on the stopper and the ground motion, which affects the amount of plastic deformation in the stopper. For a strong stopper, it will require larger forces to result in plastic deformation. Therefore, it will be easier for a stopper with less strength to dissipate energy during a relatively low seismic event than a strong stopper.

1.3 Thesis outline

In this research, both calculations and an analytical model are presented for the proposed design of a stopper-bearing system (SBS). Both ABAQUS and SAP2000 are used to simulate a bridge's response to the 1999 Chi-Chi Earthquake but now retrofitted with the stopper-bearing system. The results of the modeling are used to validate the design. Constructability of the system is an important issue and is taken into account in this paper. A series of construction steps are mentioned to give a better idea of how the stopper-bearing system could be assumed. The format of this thesis is as follows:

- Section 2 consists of a review of the existing bridge retrofits based on the issues of limiting deck displacements and problems of unseating
- Section 3 consists of the concepts on how the whole system works, detailed design concepts of each component, and their finite analysis setup in ABAQUS and SAP2000. Construction assembly of SBS is also presented in this section.
- Section 4 presents the results from ABAQUS and SAP2000 simulations
- Section 5 concludes with several important findings in this research. Future expectations and development are addressed in the end of this section.

2. LITERATURE REVIEW

2.1 Existing devices for control displacement

In order to control the displacement of decks, 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 [5]. In this section, restrainer cables and bumper blocks are introduced as examples.

A picture of restrainer cables is shown in Fig. 1, where the device aims to limit movement of bridge girders in the longitudinal direction and prevent bridge girders from unseating. Cable restrainers were first used in the United States after several bridges collapsed due to unseating during the 1971 San Fernando earthquake in California [1]. This device is easy to be installed to bridges and is effective for limiting deck displacement. However, restrainer cables are tension elements that take only tension forces. Therefore, each tendon is only able to function when in tension. To limit transverse displacement effectively, restrainer cables may not be sufficient, and other devices are necessary. In addition, restrainer cables can only pull the deck from one side of the edge. Therefore, total resisting forces on a single deck will be induced solely to one column bent and may cause damage to bridge columns.

Fig. 2 shows the bumper block, which can limit the movement of bridge decks in longitudinal and transverse direction when installed in different locations. Since bumper blocks take only compression force, the resisting force is also induced from one side of the deck and transferred to a single column bent. There are other devices designed to solve specific problems, and they have different advantages and limitations. Under major earthquakes, a bridge can face various challenges simultaneously, and a single device may be insufficient. Moreover, some devices did not function as expected in past earthquakes and revealed some deficiencies and weakness [5]. Therefore, developing a reliable and multi-functional device is desirable to add benefit to security of bridges.

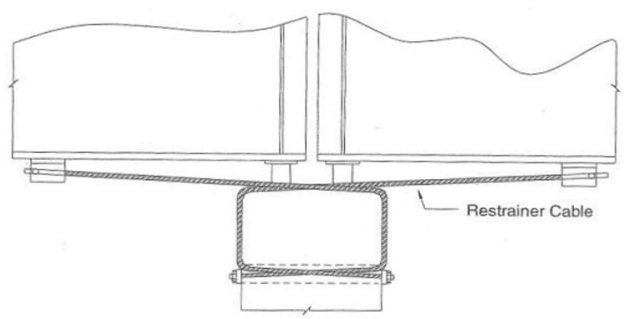


Fig. 1. Restrainer cable [5].

(Resource: Seismic Retrofitting Manual for Highway Structures: Part 1-Bridges, 2006)

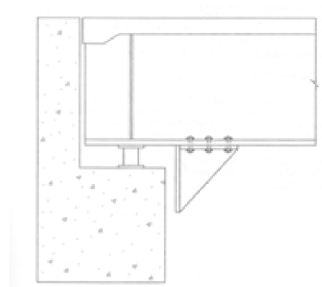


Fig. 2. Bumper block [5].

(Resource: Seismic Retrofitting Manual for Highway Structures: Part 1-Bridges, 2006)

To restrain the lateral displacement of elastomeric bearings in a slab-girder bridge, two restrainers in the form of angles or welded plates are usually placed on each side of the bearings, with a slight clearance to allow for longitudinal movement of the bearing [6]. The strategy is simple and the side restrainer can effectively limit the deck displacement in the transverse direction. Work done by Maleki [6] has suggested that stiffer restrainers are safer and do not adversely affect the substructure forces. In addition to the restrainers, other devices such as concrete shear keys and bumper blocks can also be found on bridges for limiting transverse deck displacement. However, these devices require adequate space to be installed. Therefore, a device that is able to provide reliable resistance in both longitudinal and transverse direction and require less space will serve as an ideal and economical option.

Some of the existing isolation bearings can also control the deck displacement to prevent the deck from moving forward when the designed displacement limit is reached. For example, the friction pendulum bearing can provide shear resistance and stop the deck when the deck movement in the longitudinal or transverse direction reaches the design limit. A modified friction pendulum bearing, XY-friction pendulum bearing, introduced by Marin-Artieda et al. [7] consists of two perpendicular steel rails with opposing concave surfaces and a connector can further limit the displacement in the vertical direction and prevent the bridge deck from uplifting. However, in order to obtain the advantages provided by a specific bearing system, the existing devices must be replaced. For a bridge retrofitting case, this specific bearing system must be applied to bridge to perform the displacement control function, and it is necessary to remove the existing bearings. The replacement of the existing bearings with other types of bearings may increase the cost to retrofit an existing bridge and thus decrease the number of bridges that can be retrofitted given a limited budget. An ideal solution would be a single device that has is reliable and cost-effective and can achieve expected performance. Therefore, it is valuable to propose an effective device that can work with existing isolation bearings and effectively limit the deck displacement without replacing the existing isolation bearings that already installed on the bridge. In addition, a device that is reliable and simple will require less inspection and repairs and thus serve as a cost-effective solution.

2.2 Limitations of existing methods

To stop a bridge deck effectively, high resistance may be necessary depending on the ground motion. Reliability of the device becomes a potential concern when large forces are introduced. Many bridges that were retrofitted by cable restrainers failed in both the 1989 Loma Prieta and 1994 Northridge earthquakes. 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 [5]. When these situations occur, a restrainer cable will lose its expected function and provide no protection to the bridge.

Many devices are designed to control the deck movement in a single direction; however, large displacement can happen in both longitudinal, transverse, and even vertical directions under major earthquakes. Given this situation, a single device may be insufficient to provide the bridge with adequate protection, but applying several devices in a bridge is uneconomic and may require additional maintenance reviews. A single device that can deal with deck movement in different directions will be more effective and economical.

From the above reviews, reliability of a device is the most critical point that ensures its functionality and performance during earthquakes. Each component of a device must have enough strength to provide expected resistance to stop the bridge decks. With enough stability, a device, such as SBS, is able to combine advantages of several devices that can serve as an ideal option to successfully control the displacement of bridge decks. The proposed design and analysis of the SBS is presented in the subsequent sections.

3. PROPOSED NEW DESIGN AND ANALYSIS

3.1 Design concept

In this research, a stopper-bearing system comprised of a steel stopper provides adequate lateral resistance to stop a moving deck in conjunction with a deck and base component. The stopper must be fixed firmly to a bent cap so that it can provide reliable resistance and prevent instability when pounding occurs. To successfully transfer the force, a “force receiver” should be attached to the deck to receive the resisting force provided by stopper. Therefore, a load path can be formed to transfer force from deck to substructure. The design concept of the stopper-bearing system is visualized in Fig. 3, where the system consists of three parts: deck component, stopper, and base component. Each component is described in detail in the following sections.

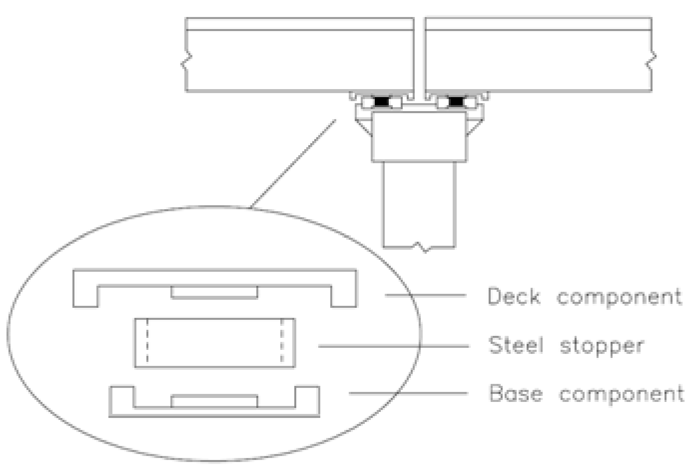


Fig. 3. Stopper bearing system at the expansion joint of a bridge.

3.2 Design details

The system consists of three parts all made of steel: 1) deck component, 2) stopper, and 3) base component as shown in Fig. 4. 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 designed to yield specific sizes of gaps depending on the anticipated horizontal displacements to achieve expected performance. The size of the base component is designed according to the size of the elastomeric bearing located in the center of the system and width of the bent cap. The base component is fixed to the bent cap like a hat by jacking the flange of the base component to the bent cap and by using bolts and tendons to ensure reliable connection. The required lateral resistance is provided by the flange when the bent cap is pushed from the side as shown in Fig. 5. Fig. 5 also indicates the relative displacement between the deck and bent cap. Inward indicates the condition when the deck moves toward the bent cap, and outward indicates the condition when the deck moves away from the bent cap. As such, the stopper is designed such that it is able to resist 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 allowable horizontal displacement. In Fig. 4, a 66-centimeter-wide steel, square stopper is shown in the center of the stopper-bearing system. The thickness of each web of stopper is 5.04

cm (2 in). The stopper fits into a steel base component, which can be replaced easily if necessary.

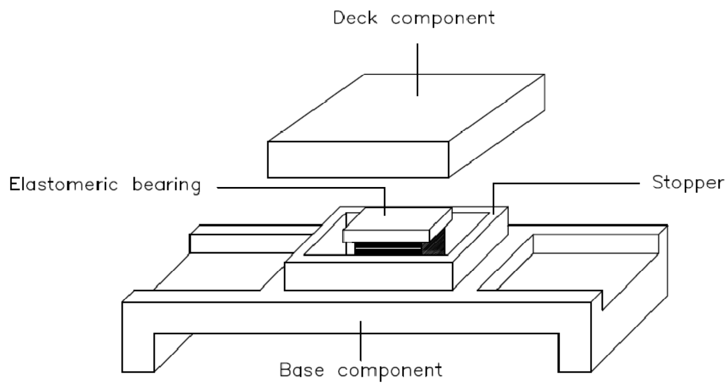


Fig. 4. Layout of stopper bearing system.

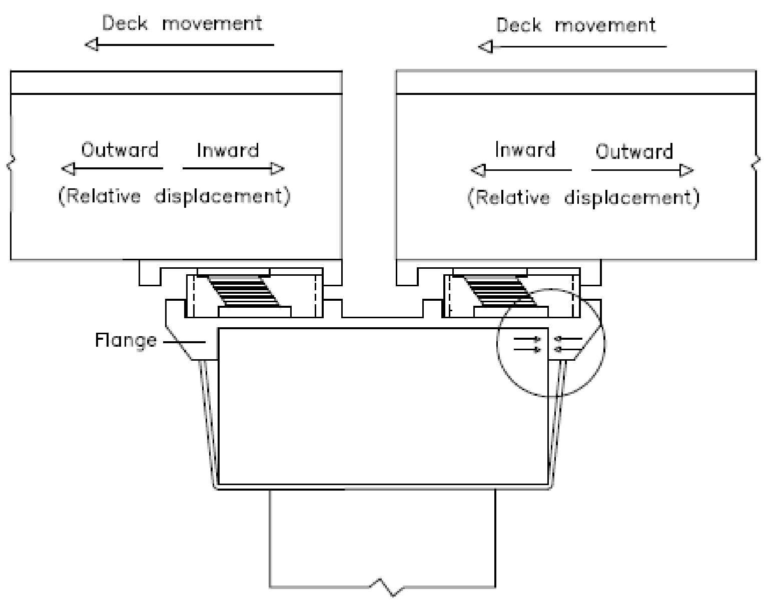


Fig. 5. Flange of deck component pushes the bent cap during pounding to transfer the lateral force to substructure.

In Fig. 6(a), the deck was initially set on top of the bearings and there is no movement. The gap widths of SBS are taken as G, which is the desirable deck displacement in each direction. However, the gap widths in each direction can be different according to the desired performance. When an earthquake occurs, the deck has a small displacement and the stopper does not interrupt the movement of the deck since such displacement does not reach the designed limitation as shown in Fig. 6(b). The deck displacement, g, is smaller than the gap width, G. In this condition, the bearing is the only component that works and dissipates energy. As the ground motion is amplified, the relative deck displacement, g, reaches the design limit, G, and the deck component contacts the stopper as shown in Fig. 6(c). 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.

During pounding between deck component and stopper, the stopper-bearing system transfers load to the columns in a similar manner in which restrainers transfer load. However, it is expected that the altered load path to the stopper-bearing system will dissipate more energy within the system. Efforts are made to study the capability of stopper to dissipate energy from its plastic deformation during pounding. Further investigations are being conducted to evaluate and quantify this phenomenon on bridges designed with the proposed stopper-bearing system given a specific demand.

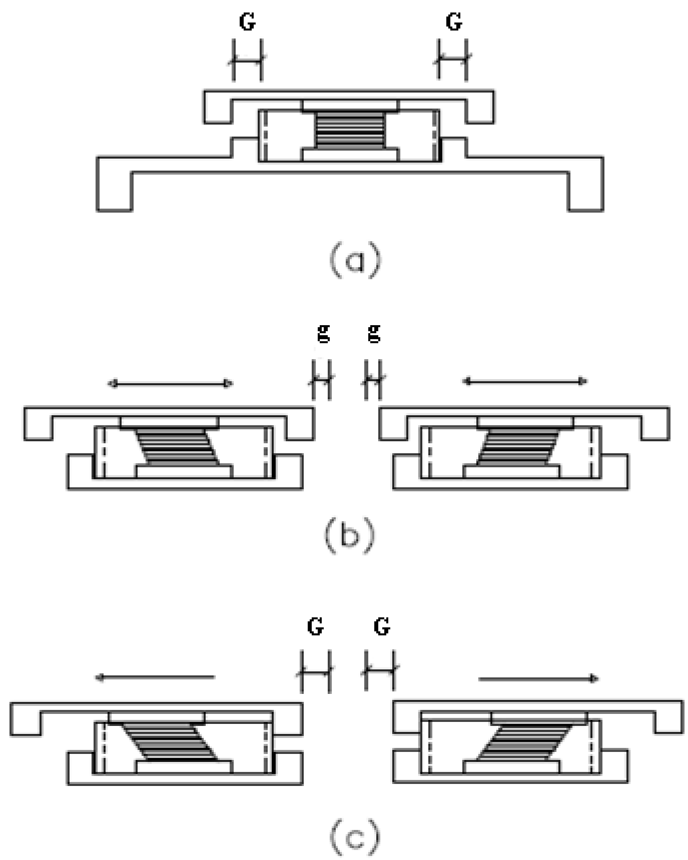


Fig. 6. Stopper bearing system in various degree of deck displacement: (a) deck initially at rest; (b) small deck displacement does not reach limitation, g < G; (c) deck movement reaches limitation, g = G.

3.2.1 Base component

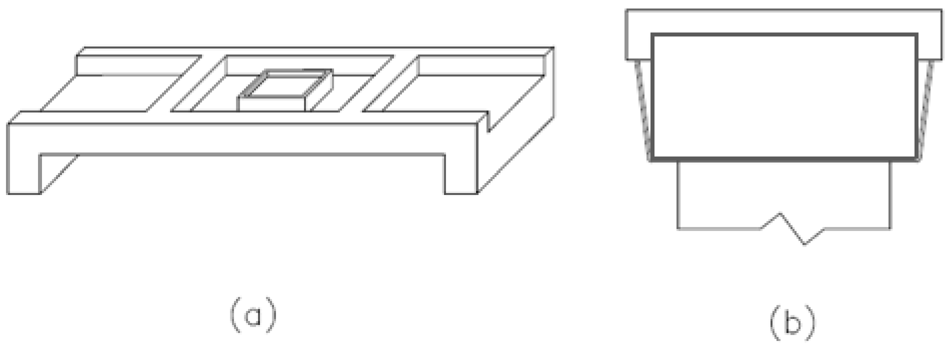


Fig. 7. Different views of base component: (a) three-dimensional view of base component; (b) connection of deck component to bent cap by tendons.

The base component shown in Fig. 7(a) is one part of the stopper-bearing system fixed to the bent cap by bolts and tendons. The bolts are designed to be on tension to prevent the base component from uplifting, while an adequate number amount of tendons are applied to tie the base component firmly to bent cap and maintain stability as shown in Fig. 7(b). Fig. 8 shows the three-dimensional view of the base component connected to bent cap by tendons. Any transverse force is transferred mainly by the flange of the base component to the bent cap as indicated in Fig. 5. In the center of the base component, a bearing seat is attached as shown in Fig. 9. The bearing fits into the slot using bolts. In addition to these bolts, the edge of the bearing seat also provides some transverse resistance to maintain the stability of the bearing under ground motion.

When movement of the deck reaches the designed limit, which is the width of the gap, G, the deck component will hit stopper, and the deck will thus stop moving ahead. In this condition, transverse force will impose a moment and make the base component rotate. To eliminate this, several tendons are connected to base component to provide resistance and resist such moment. Any transverse force and resulting moment determine the required number of tendons needed.

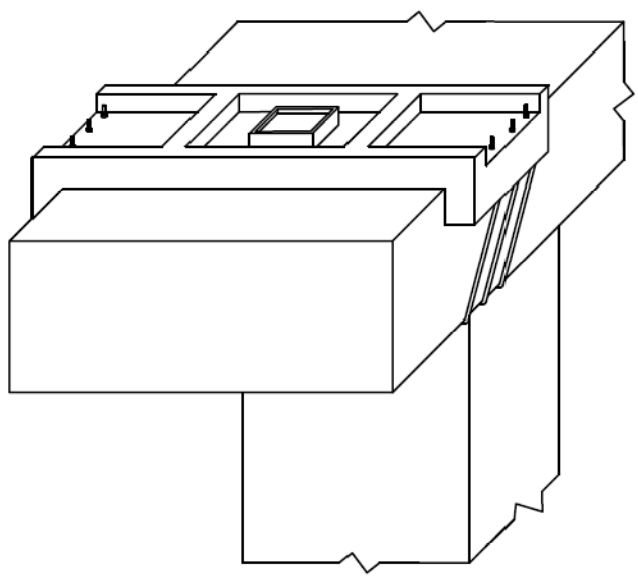


Fig. 8. Base component attached to the bent cap with tendons and bolts.

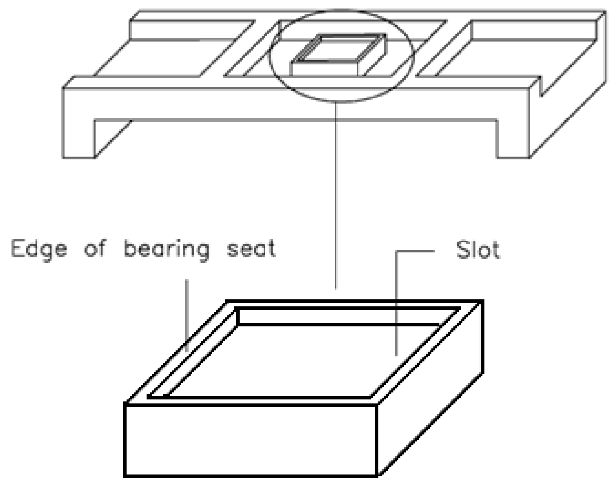


Fig. 9. Detail of the bearing seat on the base component.

3.2.2 Deck component

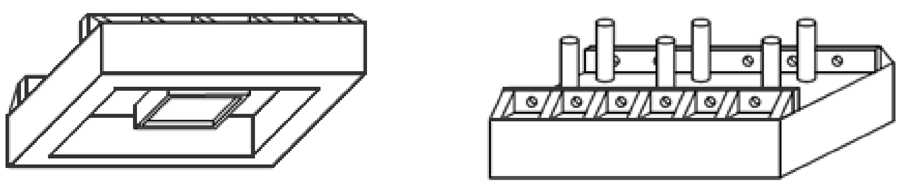


Fig. 10. 3D views of deck component.

In Fig. 10, the deck component of the stopper-bearing system is designed to be fixed to the bottom of girder. For a girder that is simply-supported, the deck component is attached at its end. For a concrete girder, steel rods that provide expected shear resistance are connected to the upper surface of the deck component, and corresponding holes are in the bottom face of girder as shown in Fig. 11. In addition, in a retrofit case, several bolts are located along both two sides of concrete girder to connect the deck component firmly to the concrete girder and transfer some of the lateral forces due to pounding when the deck component contacts the stopper. For new construction case, the deck component can be embedded into girder, and the pounding force can be transferred directly through the deck component to the girder. An issue of drilling holes under a concrete girder should be considered carefully since the deck component is designed to be much stronger than stopper typically because large deformations are only allowed in the stopper. To increase the stiffness of the deck component, addition exterior steel plates are welded as stiffeners, as shown in Fig. 12. Since the stopper is less stronger than the deck component, the deformation will happen mainly on the stopper. Once the main deformation is limited in the stopper rather than deck component or base component, the performance of this system can be predicted precisely and will be more reliable.

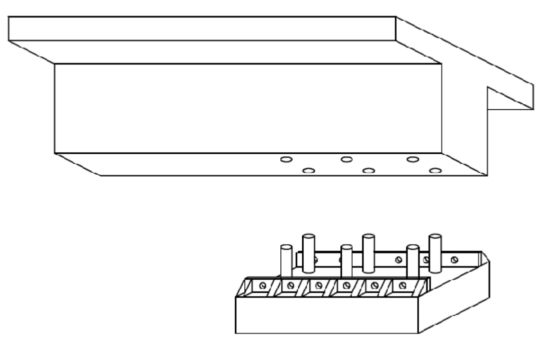


Fig. 11. Attachment of deck component and concrete girder.

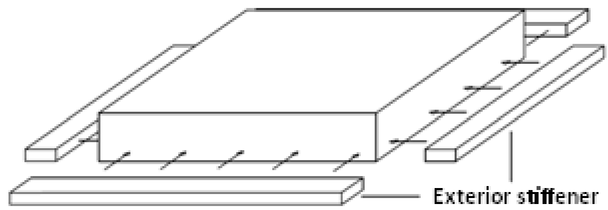


Fig. 12. Deck component and exterior stiffeners.

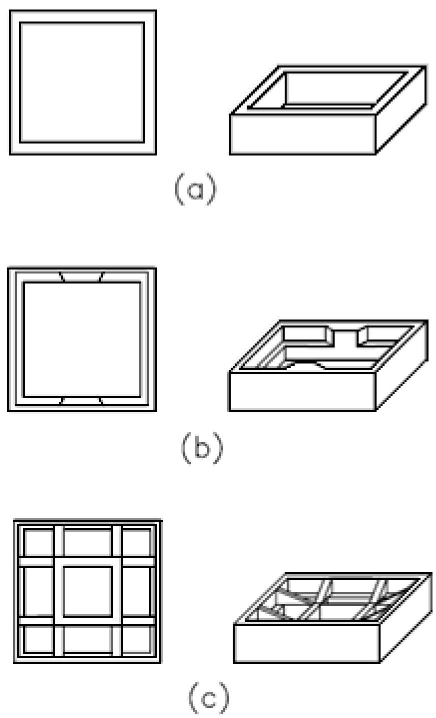


Fig. 13. Three types of stopper: (a) square stopper; (b) tapered stopper; (c) stiffened stopper.

3.2.3 Stopper - regular, tapered, and stiffened

The stopper plays an important role that controls performance of this system. The stopper is custom-designed based on the expected forces, where different plate thicknesses and layouts can provide varying stiffness to resist pounding. In addition, its stiffness determines where the plastic zone will be and how much energy the stopper can absorb. As such, there are three kinds of stoppers as shown in Fig. 13: a) regular stopper, b) tapered stopper, and c) stiffened stopper.

First, a regular stopper consists of four steel plates that are welded to become a square box. Its stiffness can be adjusted by changing the design thickness of the stopper. When thick plates are used, stiffness increases, deformation decreases, and it would be harder for plastic zone to be formed. When thin plates are used, stiffness decreases, deformation increases, and it would be easier for plastic zone to be formed and dissipate energy. However, when very thin plates are used, stability of the stopper after pounding would decrease dramatically. To solve this problem when using thin plates, a tapered stopper with different thicknesses is proposed to address this concern.

Second, a tapered stopper consists of plates with varying thicknesses. Within a tapered stopper, thin plates are applied to achieve expected performance, and thick plates are used for increasing stability. Thick plates are placed at the bottom of stopper to provide a solid and reliable base. In addition to the middle part of each side, thicker plates are used as well to improve stability. By using this kind of combination, thin plates could be used and the stability of the stopper could be maintained as well.

Third, a stiffened stopper consists of more than four steel plates, and the additional steel plates serve as interior ribs to stiffen the square stopper. By increasing the thicknesses of steel plates, the stiffened stopper can have greater stiffness than the regular type and be able to resist larger transverse forces without considerable deformations. In contrast, decreasing thicknesses of steel plates gives smaller stiffness but maintain desirable stability. According to the results provided by the ABAQUS model, the stiffened stopper can resist continuous pounding without losing its resistance significantly. However, damage can still be found in connections of steel plates in the regular, tapered and stiffened stopper after continuous pounding. It is obvious that given similar deformations, a connection that consists of two thick plates is much easier to break than a connection that consists of two thin plates because the first case possesses higher rigidity and lower ductility while being more fragile.

3.3 Assembly of SBS

The assembly or construction process is an important issue in practice. This device can either be applied as new construction or a retrofit scheme, where the construction processes are similar. To install this device, there are four components that should be assembled properly. The proposed construction methodology is in shown in Fig. 14. First, the size of base component is decided according to the size of the elastomeric bearing and the width of bent cap. This component can easily fit onto a bent cap through the bolt connections and tendons. 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 fixed, the elastomeric bearing fits into a slot on the bearing seat of the base component and is positioned or connected into place by bolts. The stopper is then placed into the base component and the bearing is centered on the base component. The deck component can then be placed on top of the bearing and connected by bolts from the top. Finally, the girders can be placed on the deck component and the bolts can be connected. If any component needs to be replaced, it is easy to reverse the construction process to the target step and make the replacement.

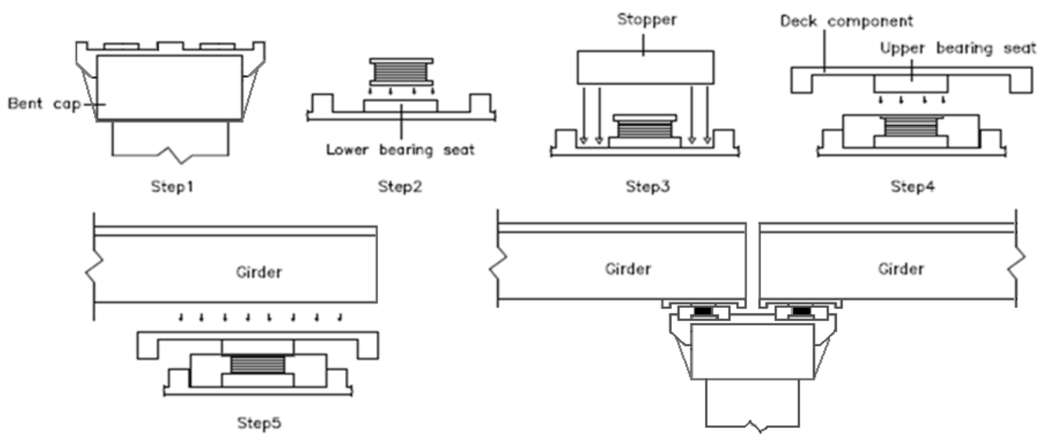
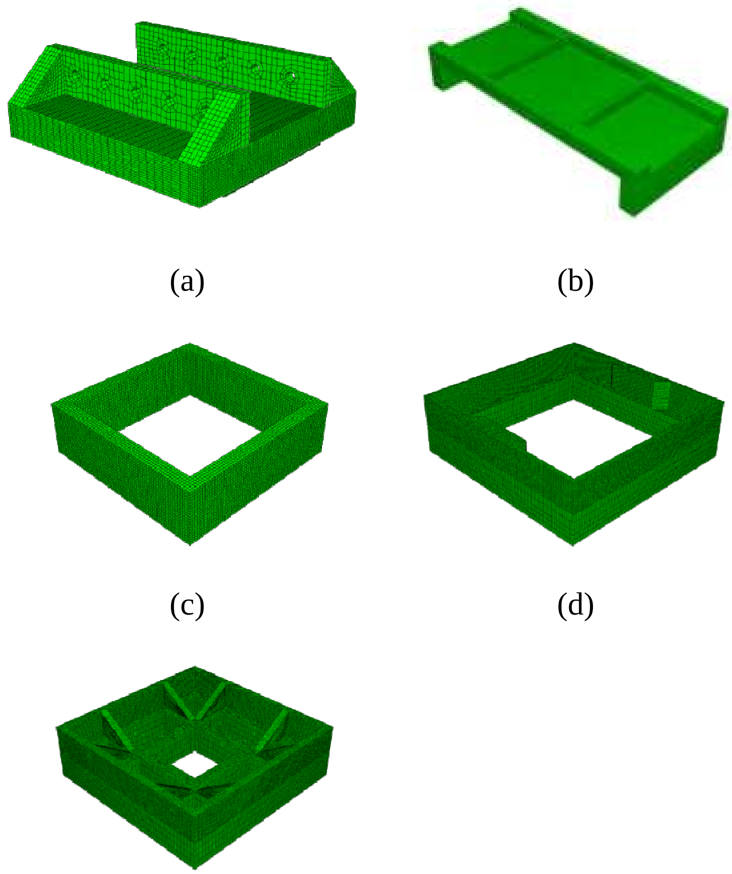


Fig. 14. Assembly of SBS.

3.4 Analytical modeling using ABAQUS and SAP2000

3.4.1 SBS components using ABAQUS



(a) (b)

(c) (d)

(e)

Fig. 15. Components simulated in ABAQUS: (a) deck component, (b) base component, (c) square stopper, (d) tapered stopper, (e) stiffened stopper.

In this research, computer simulations using the finite element method are performed by ABAQUS. The deck component and stopper (regular, tapered, stiffened) in Fig. 15 are simulated individually, and a complete model of the entire system is also constructed. When simulating various components individually, some boundary conditions are assumed reasonably since other parts of the system are not presented. Interested and expected deformations are assigned in each simulation as controlled parameters to investigate the capacity of the component of interest and response of the testing component. When simulating the whole system, displacement of the deck, which is the same as movement of the top of the deck component, is taken as the controlled parameter to predict the response of SBS. The bent cap of bridge is modeled using solid elements, and the whole system sits freely on it. Pounding force and pressure between the different components is generated by a contact function in ABAQUS. In this model of the entire system, the tendons applied to hold the base component are simplified by pinning the ends of flanges of the base component. The forces in the tendons are determined by the vertical reaction force at the pinned ends. The required area of tendons is determined accordingly. In this study, a square stopper is used as an example, and the deck component is square as well. Note that the size and shape of each component should be designed according to the expected and subjected to change should the demand exceed the capacity of the initial design. In this model, the outer dimension of the stopper is 66 cm (26 in), and the thickness of the plates is subjected to change in different types. For the deck component, the interior size is taken as 86 cm (33.86 in), which gives a space of 10.16 cm (4 in) between stopper and deck component. Therefore, the width of gap is 10.16 cm (4 in). When the deck movement exceeds this value, the gap closes, and contact between stopper and deck component occurs. Transverse force is then transferred through the system to substructure of bridge.

3.4.2 SAP2000 modeling of bridge response

Three simply-supported bridge models are constructed in SAP2000 to evaluate their performances when equipped with a stopper-bearing system. The three bridge models include a one-span 3D bridge model (Fig. 16), two-span 3D bridge model (Fig. 17) and three-span 3D bridge model (Fig. 18). Major components of these bridge models are the same except the number of spans. Like a typical bridge, each bridge model has a superstructure, substructure, and bearings under each girder. In this research, there are two stopper-bearing systems equipped symmetrically at each end of each deck.

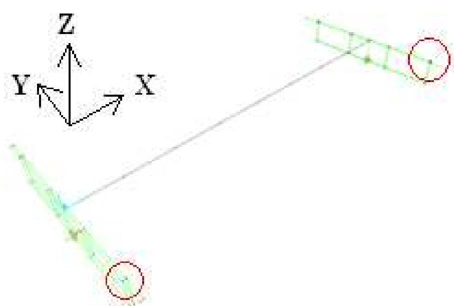


Fig. 16. One-span simply-supported bridge model in SAP2000.

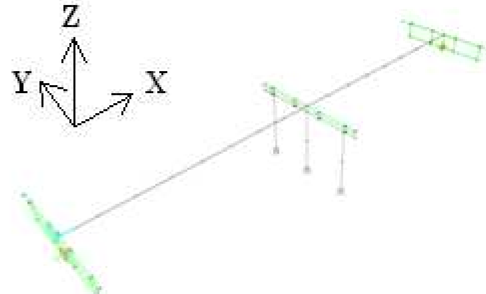


Fig. 17. Two-span simply-supported bridge model in SAP2000.

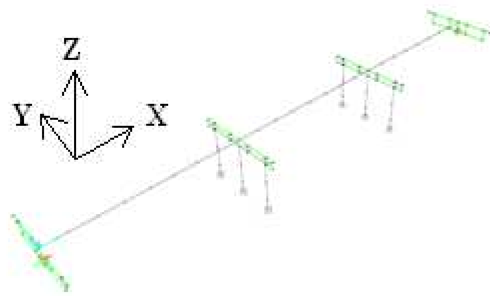


Fig. 18. Three-span simply-supported bridge model in SAP2000.

3.4.2.1 Superstructure

A one-span, two-span and three-span simply-supported concrete girder bridge model is constructed in SAP2000 to investigate how the stopper-bearing system changes their seismic performance. The superstructure as shown in Fig. 19 consists of four 121.9 centimeters-deep concrete Tee beams with a slab of 30.5 cm (12 in). Total width of bridge deck is 10.97 m (36 ft) and length of each bridge deck is 21.33 m (70 ft). Distance between adjacent girders is taken as 2.95 m (9.67 ft). Beneath each girder, there is an elastomeric bearing.

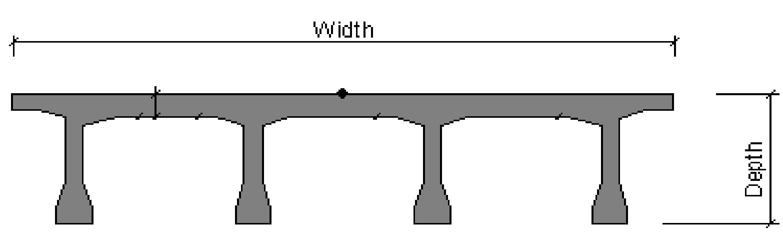


Fig. 19. Cross-section of superstructure.

3.4.2.2 Substructure

Substructure of this bridge consists of three-column bridge bents. Each column has a square cross-section. Its width is 106.7 cm (3.5 ft), and the height of column is 609.6 cm (20 ft). Seven #11 longitudinal bars are in each side of the column, and #5 bars are served as confinement bars with space of 15.24 cm (0.5 ft). The clear cover is 10.16 cm (4 in). Support condition for column bents and abutments are assumed to be fixed to the ground. The main purpose of this model is to investigate the seismic performance of bridge before and after installing the stopper-bearing system.

3.4.2.3 Stopper-bearing system (SBS)

In this bridge model, four stopper-bearing systems are applied under each deck segment, two at each side. Stopper-bearing system is simulated by the Takeda multi-linear plastic element that is defined in SAP2000 [8]. This system is located between the deck and bent cap and connected with rigid link elements to capture pounding between deck component and stopper. The deck component is designed much stronger than the stopper; therefore, the plastic deformation resulting from pounding between them is assumed to appear solely in the stopper. The deformation of deck component is captured by the Takeda multi-linear plastic elements. It shows the nonlinear behavior of the stopper under pounding. Force-displacement behavior of the stopper subjected to external force is obtained from ABAQUS first, and then its force-displacement relationship is specified in the nonlinear plastic element. Each stopper-bearing system consists of two Takeda multi-linear plastic elements - SBS Compressive Member and

SBS Tensile Member. The SBS Compressive Member captures the behavior of SBS when deck moves toward bent cap, and the SBS Tensile Member captures the behavior of SBS when deck moves away from bent cap. A SBS Compressive Member and a SBS Tensile member for type1 SBS with 2.54 cm (1 in) gap are presented in Fig. 20 and Fig. 21 as examples. Both these two members include a zero-stiffness zone in the initial part to represent the widths of gaps. When pounding happens during deck moving excessively towards bent cap, the deformation in Takeda Compressive Member will exceed the zero-stiffness zone, enter elastic zone, and provide lateral resistance. While the deck keeps moving forward, the stopper might have permanent deformation, and the SBS Compressive Member enters its plastic range accordingly. The same behavior happens when the deck moves excessively away from the bent cap. These two mechanisms represent the whole response of the stopper-bearing system when subjected to a ground motion.

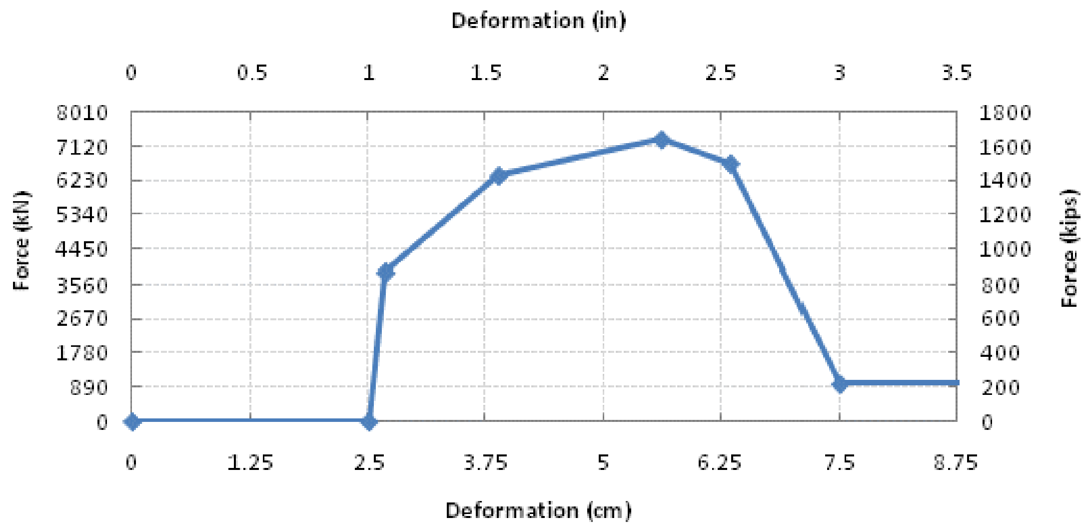


Fig. 20. SBS Tensile Member of stopper-bearing system with stopper type1 and 2.54 cm (1 in) gap.

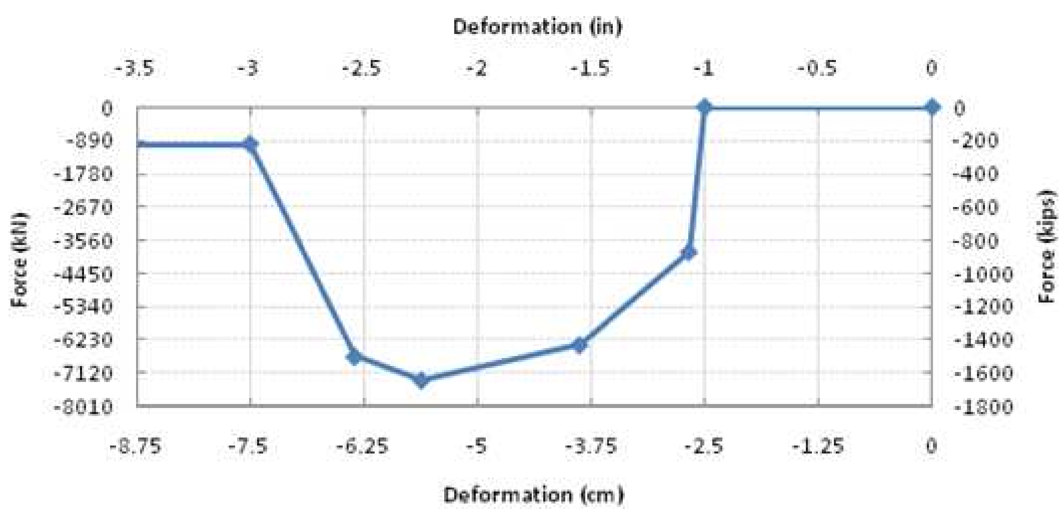


Fig. 21. SBS Compressive Member of stopper-bearing system with stopper type1 and 2.54 cm (1 in) gap.

3.4.2.4 Elastomeric bearing

Elastomeric bearings are the energy dissipating elements placed beneath each bridge girder. Behavior of elastomeric bearing is simulated by multi-linear plastic element, which is built in SAP2000. The force-displacement data of the bearing is referenced from previous work done by other researchers [9]. This referenced data is then modified according to the conditions of bridge models. Fig. 22 shows the force-displacement relationship of elastomeric bearing used in this research.

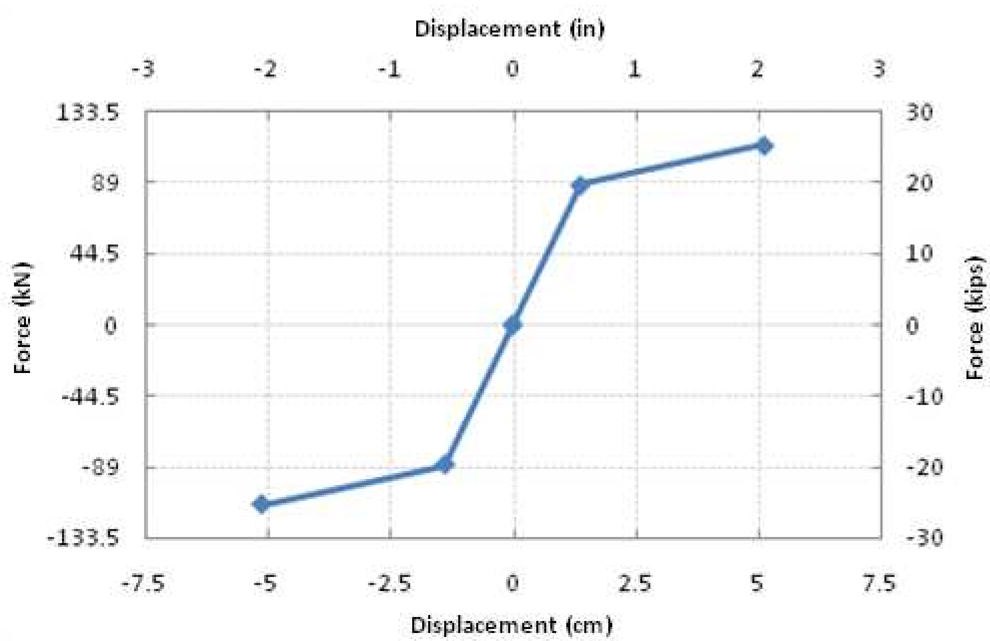


Fig. 22. Force-displacement relationship of elastomeric bearing.

3.4.2.5 Ground motions

Two ground motion histories of the Chi-Chi earthquake (Taiwan, 1999) recorded at station TCU084 are used. The stronger ground motion occurred in the east-west direction has peak ground acceleration (PGA) of 1.01g. The other ground motion, which occurred in the north-south direction, has PGA of 0.43g. In this research, both ground motions are applied respectively to the bridge models in SAP2000 to investigate their responses. Fig. 23 and Fig. 24 show the time histories of accelerations of these two earthquakes.

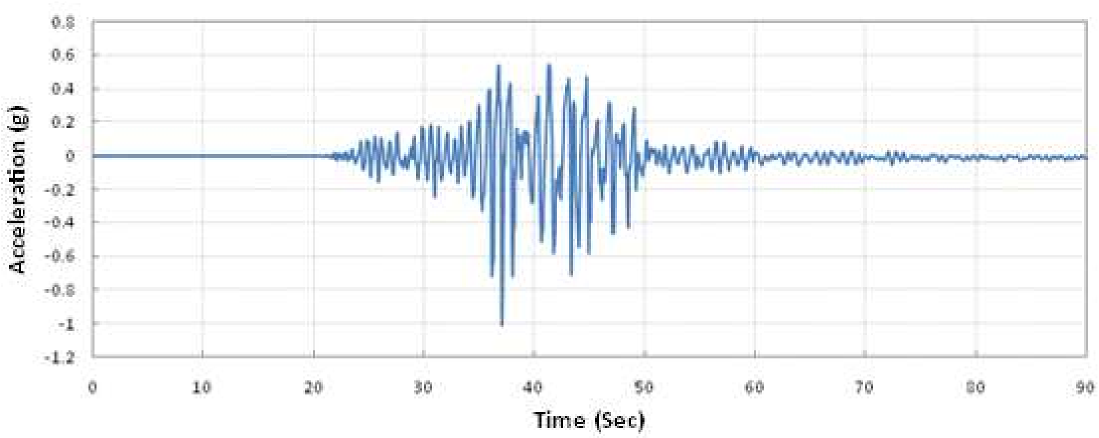


Fig. 23. Time-history of Chi-Chi earthquake (1.01g – E-W component).

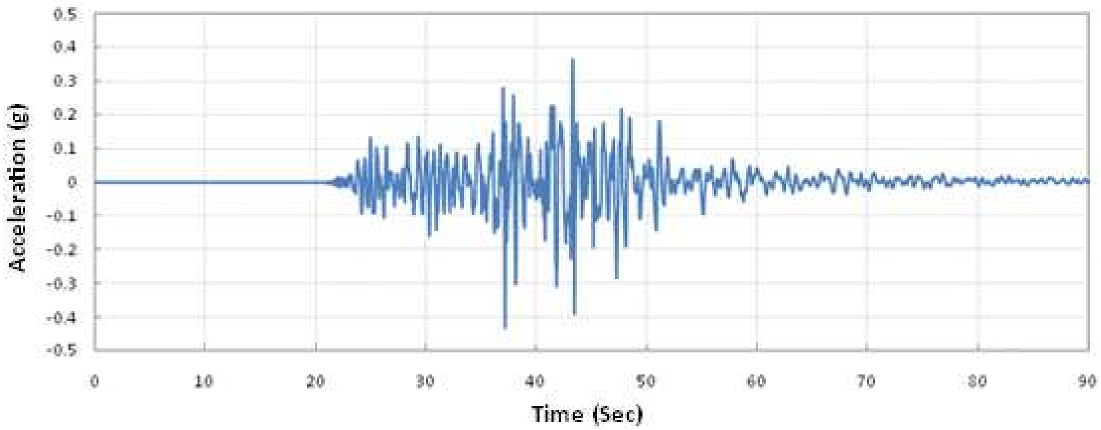


Fig. 24. Time-history of Chi-Chi earthquake (0.43g – N-S component).

3.4.3 Types of stoppers

In SAP2000 simulation, behaviors of four types of stiffened stoppers are applied to bridge models. Although more than four stoppers are studied in the ABAQUS simulations, the selected types can suitably represent different levels of resistances. These four types are type1, type3, type5, and type6, and all six types will be discussed in Section 4. Type1 provides largest resistance among them and type6 provides the least. Load-deformation relations generated by ABAQUS for the four stoppers and their corresponding simplified model used in SAP2000 are presented. Fig. 25, Fig. 27, Fig. 29 and Fig. 31 are load-deformation relations obtained from ABAQUS. Fig. 26, Fig. 28, Fig. 30 and Fig. 32 are simplified load-deformation relationships of these four types of stoppers.

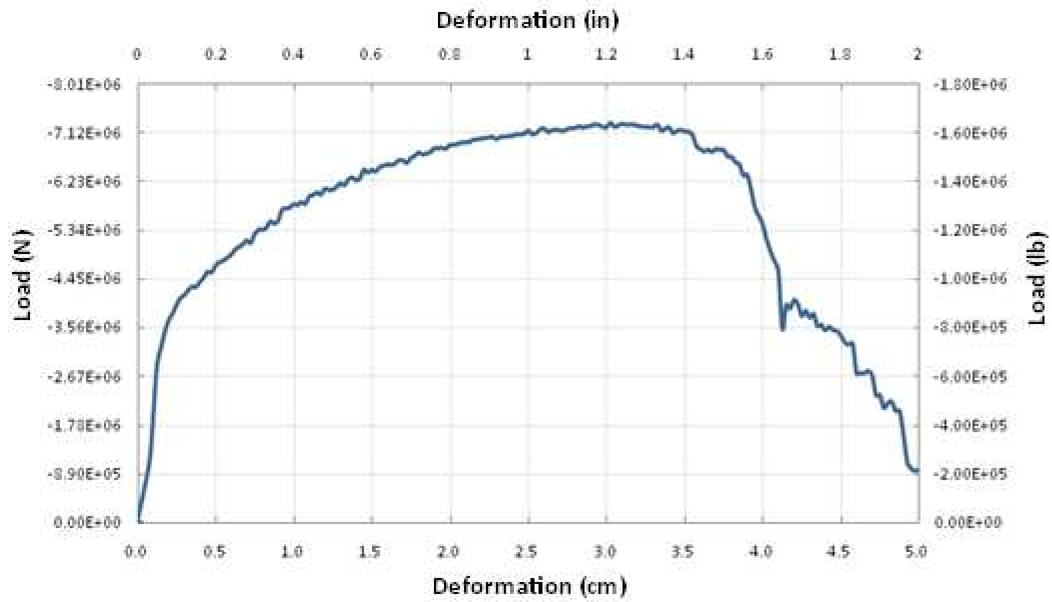


Fig. 25. Load-deformation relationship of stiffened stopper type1.

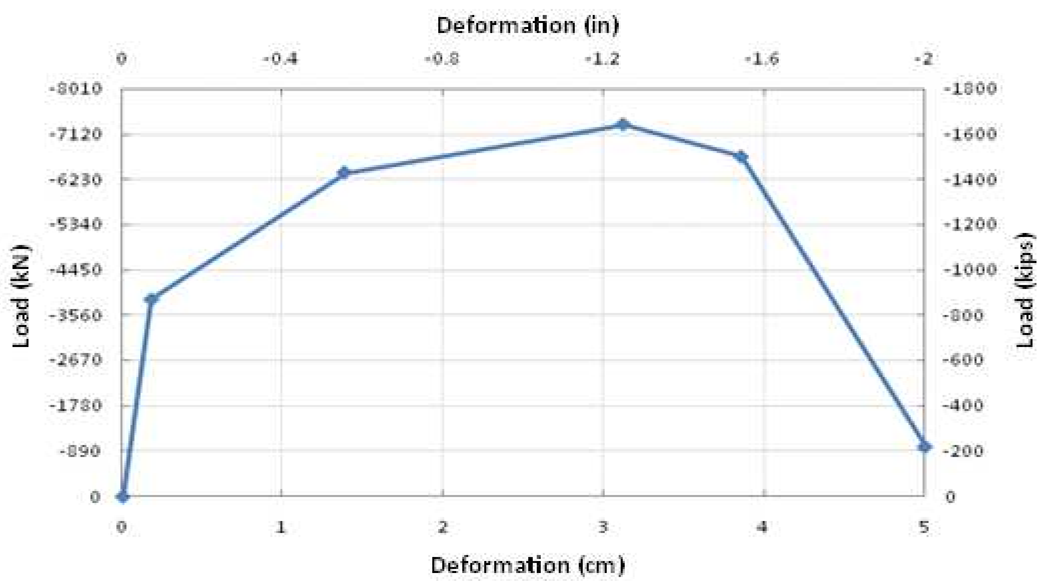


Fig. 26. Simplified load-deformation relationship of stiffened stopper type1.

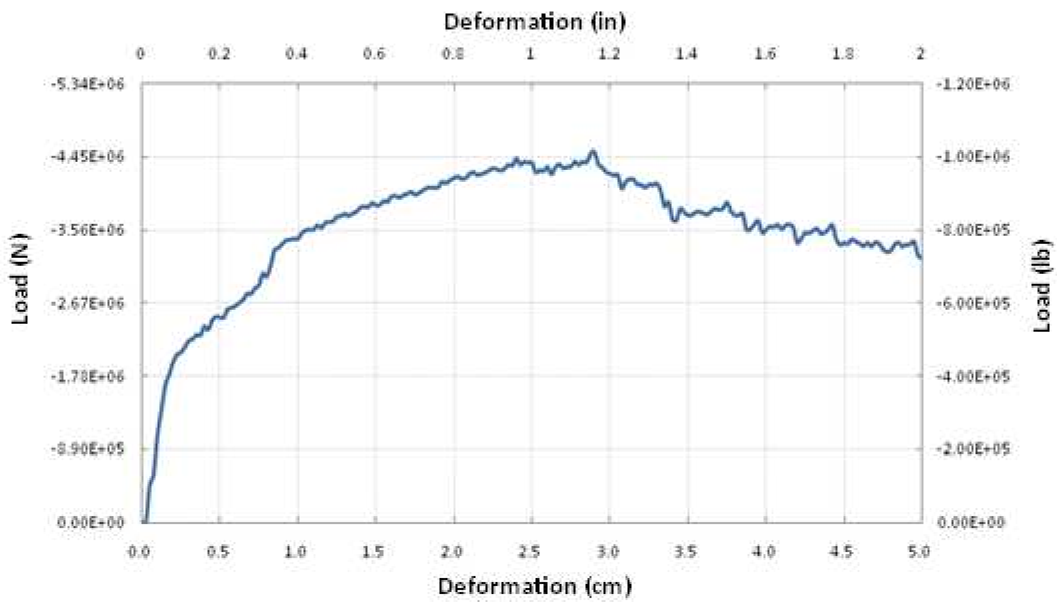


Fig. 27. Load-deformation relationship of stiffened stopper type3.

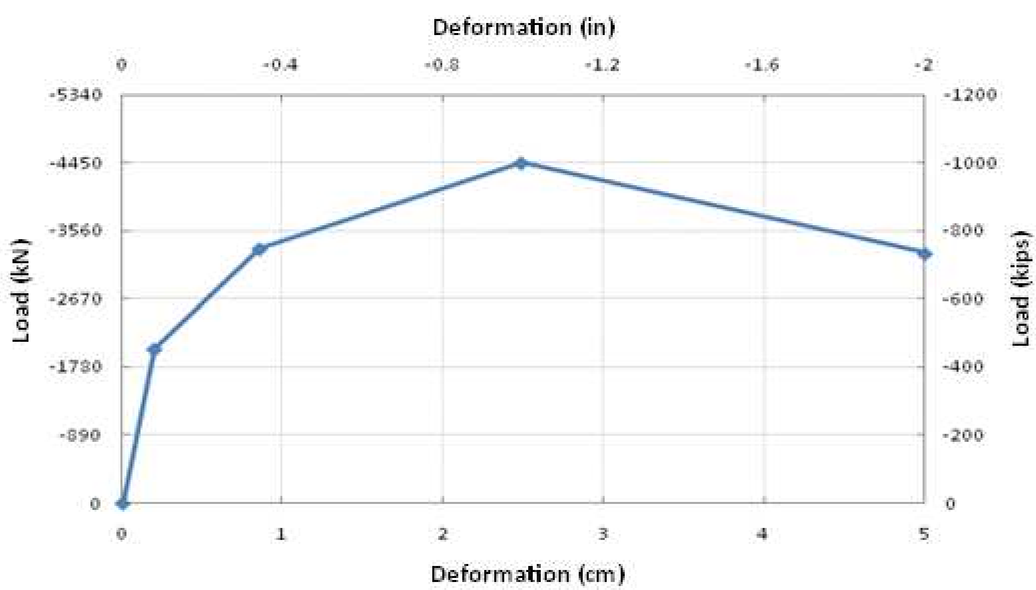


Fig. 28. Simplified load-deformation relationship of stiffened stopper type3.

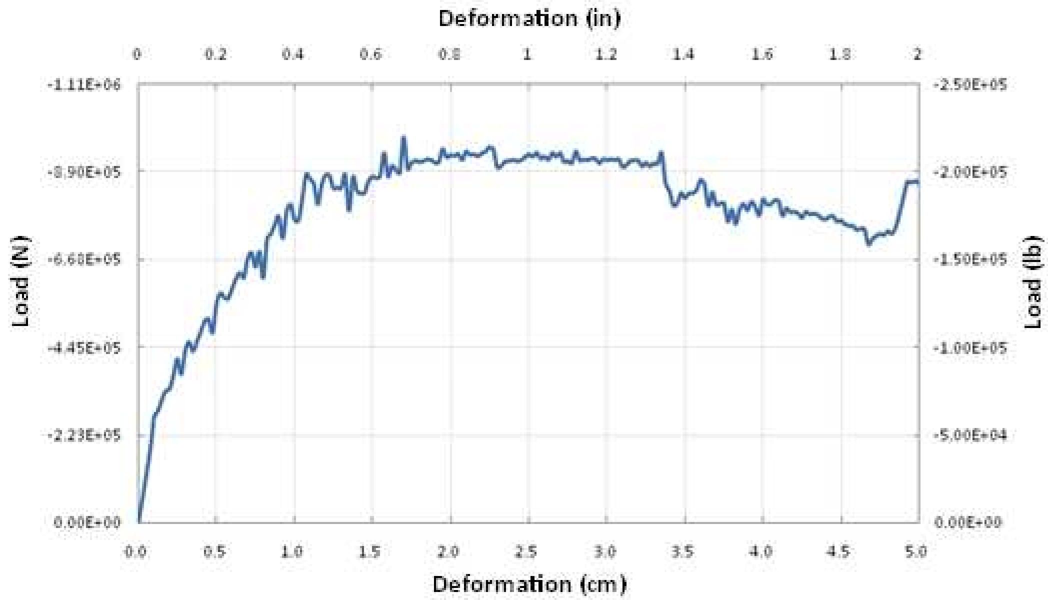


Fig. 29. Load-deformation relationship of stiffened stopper type5.

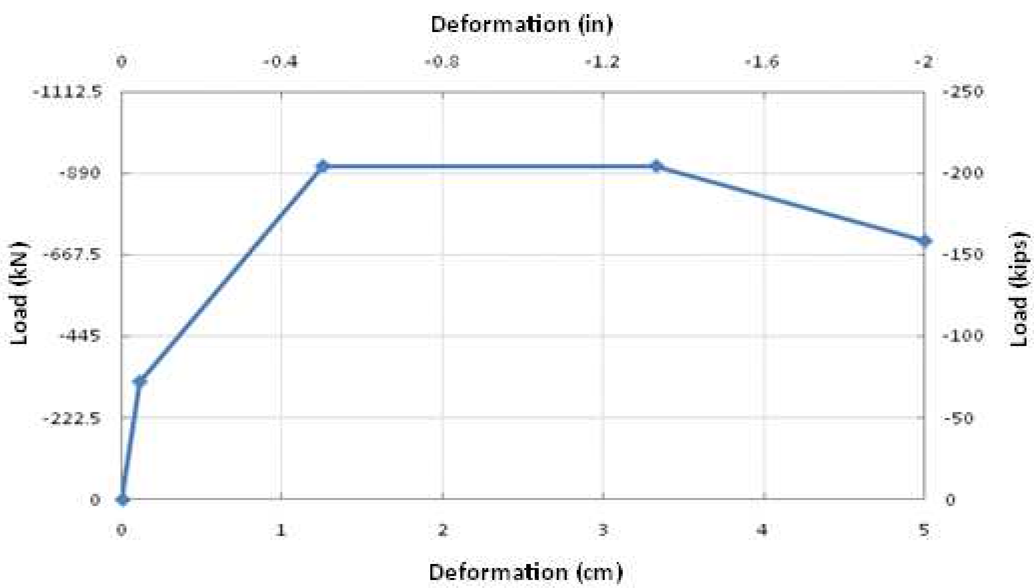


Fig. 30. Simplified load-deformation relationship of stiffened stopper type5.

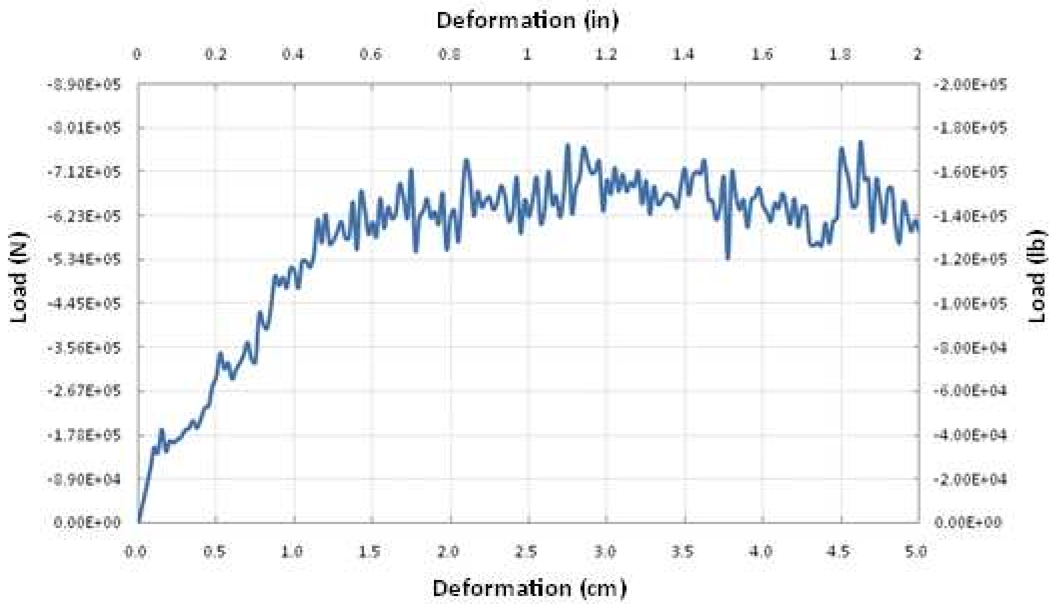


Fig. 31. Load-deformation relationship of stiffened stopper type6.

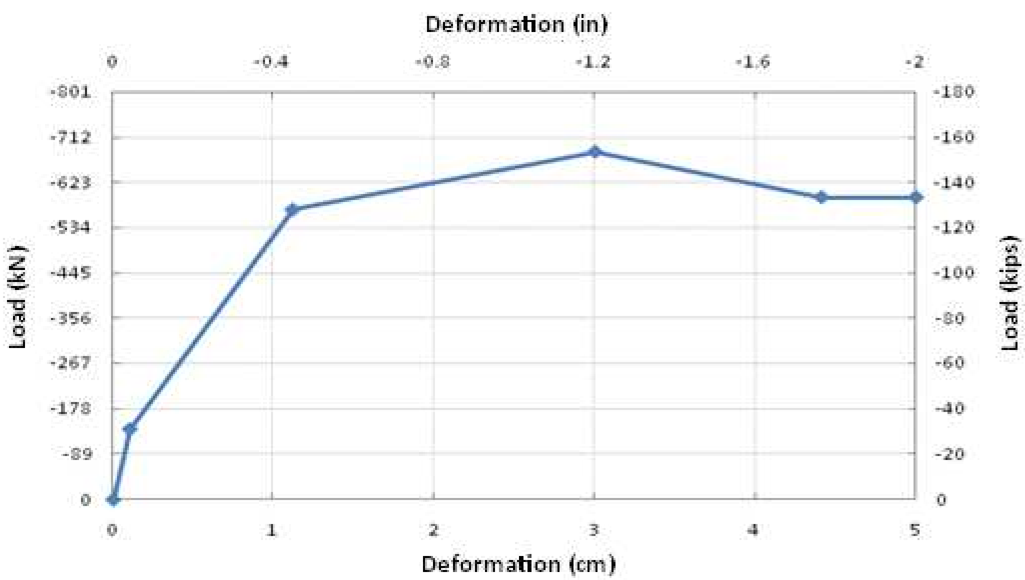


Fig. 32. Simplified load-deformation relationship of stiffened stopper type6.

4. RESULTS AND ANALYSIS

4.1 Results from ABAQUS

4.1.1 Base component and tie force

The base component is modeled in ABAQUS with the entire SBS because its behavior relates to the interaction between stopper and deck component. It is not appropriate to model this component individually. In this model, base component rests on rigid bent cap and its flanges are pinned at the ends. The reaction forces generated at the pinned support represent the holding force provided by steel tendons. In this analysis, the movement of deck component is specified to contact the stopper and keep moving forward 1 cm (0.4 in). Reaction force generated at the pinned support is 1650 kN (371 kips). The required number of tendons based on their area can be designed according to the result. From the result, two high stress concentration areas can be found in the base component at locations where the stopper contacts it as shown in Fig. 33. Thickness of the wall of the stopper seat, which is the steel retaining wall surrounds the stopper, determines its capability to resist the transverse force transferred from stopper. In this analysis, thickness of the retaining wall is taken as 5 cm (2 in), and it can resist the transverse force without damage. The thickness of the base component is 5 cm (2 in). Since the width of base component is 76.2 cm (30 in), the cross-sectional area of the base component provides enough capability to resist the pounding forces in this analysis. The dimensions of each part should be designed according to expected transverse force.

Flanges at the ends of base component are major parts that transfer transverse forces to the substructure of bridge. To avoid local damage at the contact area on bent cap, the length of flanges should be long enough to spread the transverse force.

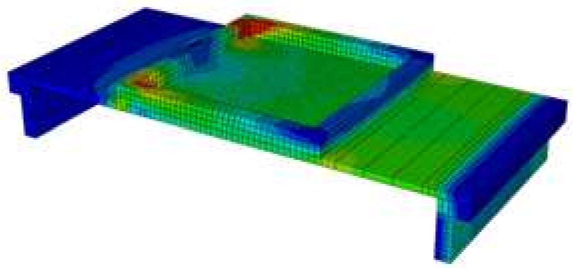


Fig.33. Stress concentration on base component caused by the force transferred from stopper.

4.1.2 Deck component

There are two simulations for deck component in ABAQUS. One includes the whole stopper-bearing system to investigate the performance of the deck component, and the other model includes solely the deck component. Several iterations were conducted to determine the resistance provided by the deck component based on its thickness. In the displacement control analysis of the entire stopper-bearing system, the deck component contacts the stopper in the beginning and keeps moving 1 cm (0.4 in) ahead. The deck component without an exterior stiffener (Fig. 34) has a maximum deformation of 0.65 cm (0.26 in), which is larger than the deformation of stopper, 0.35 cm (0.14 in). This indicates that lateral stiffness of plate deck component is not enough.

In the end of the pounding process, the maximum contact force transferred is 3500 kN (787 kips).

In the other analysis, an exterior stiffener is attached to deck component as shown in Fig. 35. The width of this exterior stiffener is 5 cm (2 in), and its thickness is 2.54 cm (1 in). Deformation in the deck component decreases to 0.53 cm (0.21 in), and deformation of stopper becomes 0.47 cm (0.19 in). The deformation of a stiffened deck component decreases about 19 percent. Note, thickness of the side plates of deck component is 5 cm (2 in).

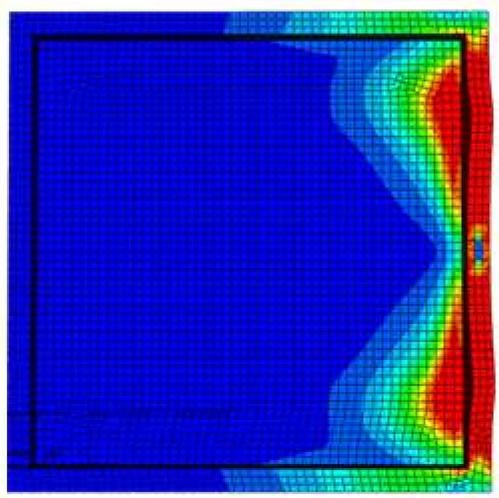


Fig. 34. Stress contour of deck component without exterior stiffener subjected to 1 cm (0.4 in) deformation.

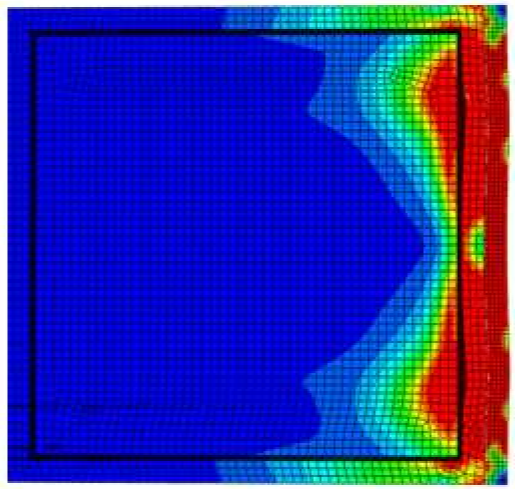


Fig. 35. Stress contour of deck component with exterior stiffener subjected to 1 cm (0.4 in) deformation.

From the ABAQUS simulations, the exterior stiffener increases the stiffness of the deck component and yields a desirable result. A further investigation on exterior stiffener is conducted. With different dimensions, exterior stiffeners increase the deck component's stiffness and decrease deformation. Fig. 36 shows the details of the exterior stiffener. In this investigation, deck components are fixed on part of their top surface and pushed by a rigid object. Fixed areas on the top surface represent connections to girder. Rigid objects are applied in these models to eliminate deformation generated by stopper and to provide better results. It has same contact area as stopper. The rigid object is controlled to move ahead and create a 1.27 cm (0.5 in) deformation in the deck component. There are seven models in this investigation and their dimensions are shown in Table 1.

The force-displacement relationship is shown in Fig. 37. The part of interest in this figure starts from deformation of 0.5 cm (0.2 in) to 1.27 cm (0.5 in), which is the flat part of curve. These values indicate capacities of different deck components analytically, which serve as guidelines in the design. In this figure, curves can be roughly divided into three groups according to their thickness. Although deck components equipped with exterior stiffeners will increase stiffness, thickness of deck component influences their performance more significantly. Results of these types are compared in Table 2.

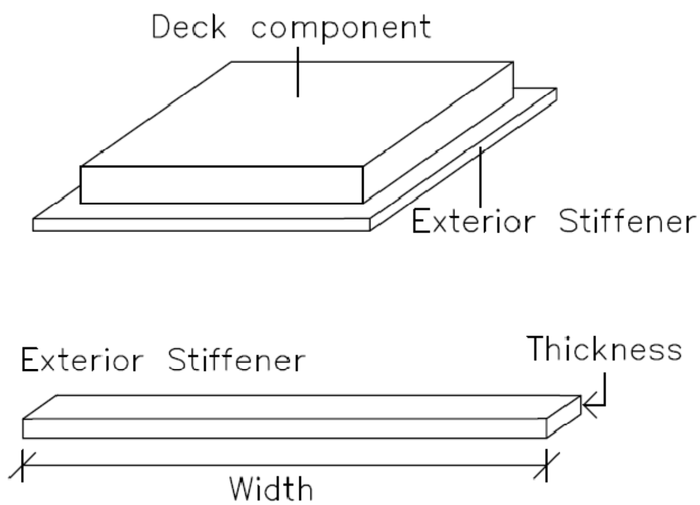


Fig. 36. Details of the exterior stiffener.

Table 1
Geometries of deck components.

Type	Thickness of flange (cm)	Exterior stiffener	Exterior stiffener thickness (cm)	Exterior stiffener width (cm)
1	5.08	X	N/A	N/A
2	5.08	O	2.54	5.08
3	5.08	O	2.54	10.16
4	5.08	O	5.08	5.08
5	5.08	O	5.08	10.16
6	7.62	X	N/A	N/A
7	2.54	X	N/A	N/A

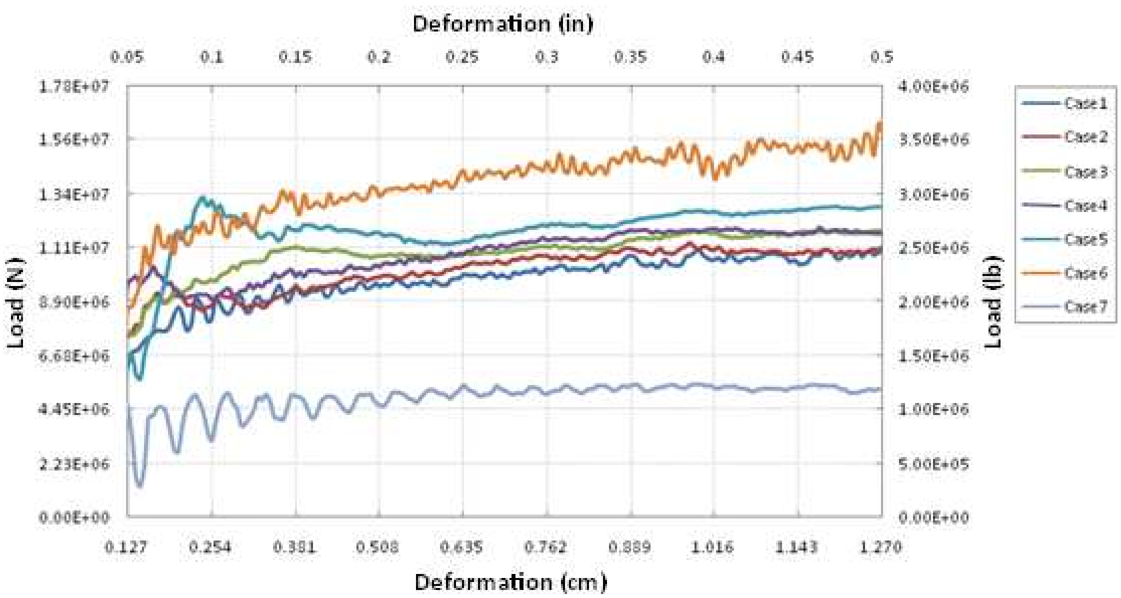


Fig. 37. Load-deformation relationship of deck component.

Table 2
Performance after applying various exterior stiffeners.

Type	Thickness (cm)	Width (cm)	Force (kN)	Percentage (%)
1	N/A	N/A	10290	100%
2	5.08	5.08	10795.7	105%
3	2.54	10.16	11164.6	109%
4	5.08	5.08	11419.1	111%
5	5.08	10.16	12023.7	117%

N/A : No stiffener applied.

Table 3
Effects by various thicknesses.

Type	Thickness (cm)	Force (kips)	Percent Reduced
1	5.08	10290	100%
6	7.62	14668	143%
7	2.54	5059.4	49%

Values in Table 2 are forces required to generate 0.762 cm (0.3 in) deformation in deck components. From this comparison, the strongest stiffener in Type5 increases force capacity to 117%, and other stiffeners increase in their force capacity slightly. Therefore, increasing the thickness of deck component would be a suitable option to increase force capacity significantly. Comparison of the different capacities provided by various thicknesses is shown in Table 3. The data shows that a deck component with 5-centimeter-thick web possesses a force capacity of 10290 kN (2313.3 kips). In Type6, the thickness is increased to 7.62 cm (3 in), and its force capacity increases to 14668 kN (3297.6 kips), which is 143% of the result of Type1. The same trend applies to Type7, the force capacity decreases to 49% of Type1. The force capacity is almost promotional to thickness of deck web. Their relationship is shown in Fig. 38.

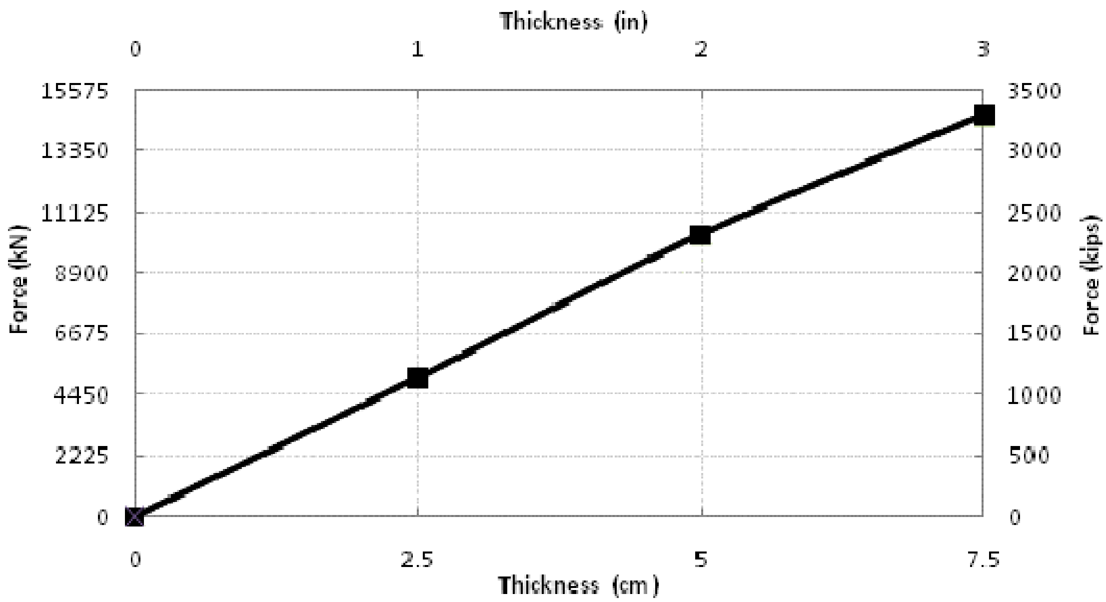


Fig. 38. Relationship between capacity of the deck component and its thickness.

4.1.3 Stopper - regular, tapered and stiffened

Three types of stoppers are simulated individually. In this analysis, the modeling includes a stopper and a rigid deck component. The stopper is properly confined by assumed boundary conditions to represent the confinement provided by base component. By these assumptions, behavior of stopper under pounding can properly be simulated, and it takes less time to obtain results. With the rigid deck component, plastic deformation occurs solely in stopper, and the result can precisely reflect the properties of the stopper without noise from deformation in deck component.

The first type of stopper consists of a regular stopper with all web thicknesses of 5.08 cm (2 in) as shown in Fig. 39. A rigid deck component hits the fixed stopper and causes a 5.08 cm (2 in) deformation as shown in Fig. 40. In this pounding process, the response is recorded to generate corresponding load-deformation curve. (Fig. 41)

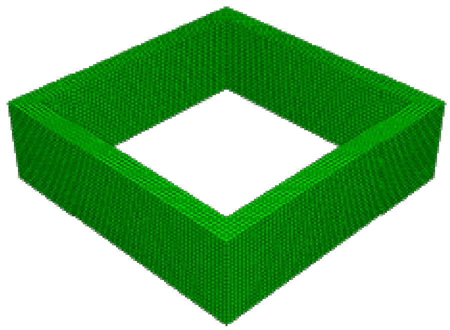


Fig. 39. 5.08 cm (2 in) thick square stopper.

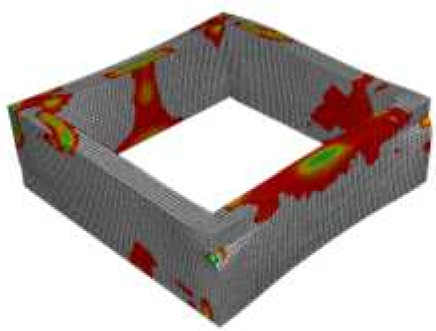


Fig. 40. Stress contour of the 5.08 cm (2 in) thick square stopper subjected to 5.08 cm (2 in) deformation.

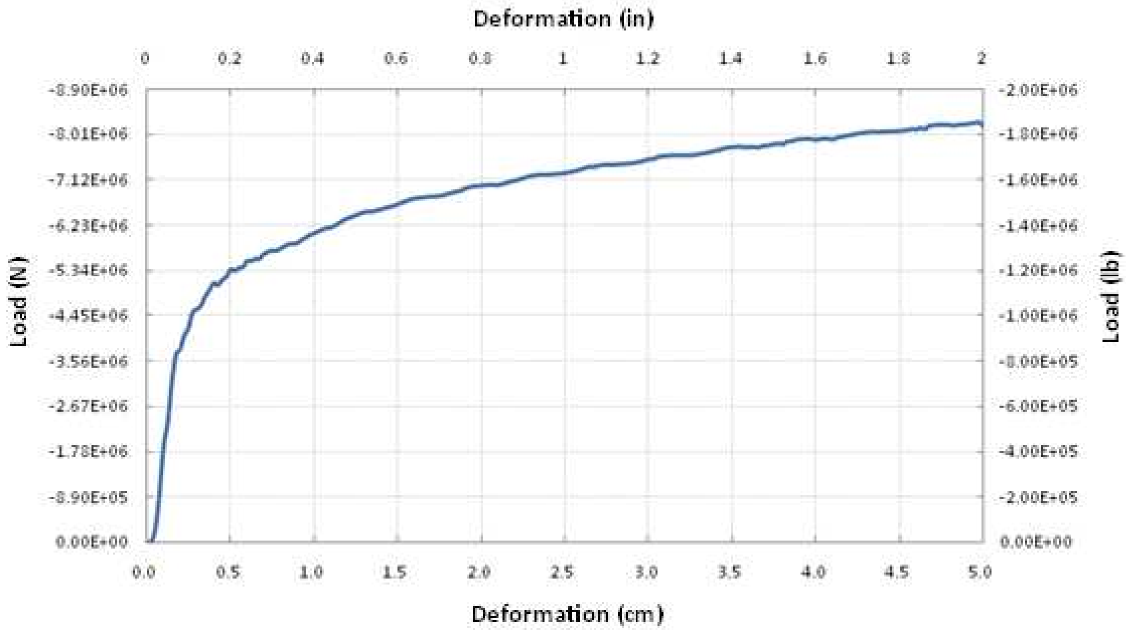


Fig. 41. Load-deformation relationship of the 5.08 cm (2 in) thick square stopper subjected to 5.08 cm (2 in) deformation.

Fig. 42 shows another type of a thinner web with all web thicknesses of 1.27 cm (0.5 in). In this type, thinner stopper provides smaller capacity, and it becomes unstable after pounding by deck component, as shown in Fig. 43. Its load-deformation curve is shown in Fig. 44. From the result, it suggests that a tapered stopper with stronger stiffness and stability would serve as a better option when applying thin-web stopper.

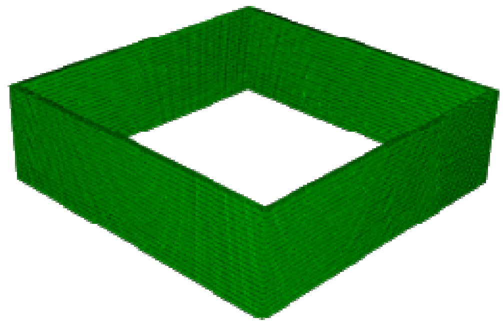


Fig. 42. 1.27 cm (0.5 in) thick square stopper.

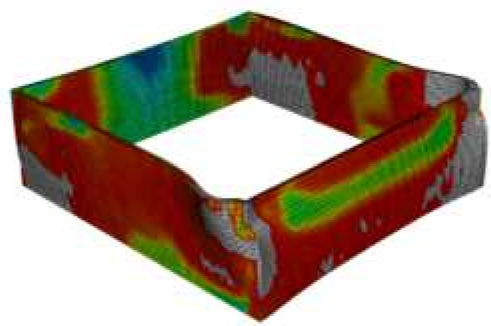


Fig. 43. Stress contour of the 1.27 cm (0.5 in) thick square stopper subjected to 5.08 cm (2 in) deformation.

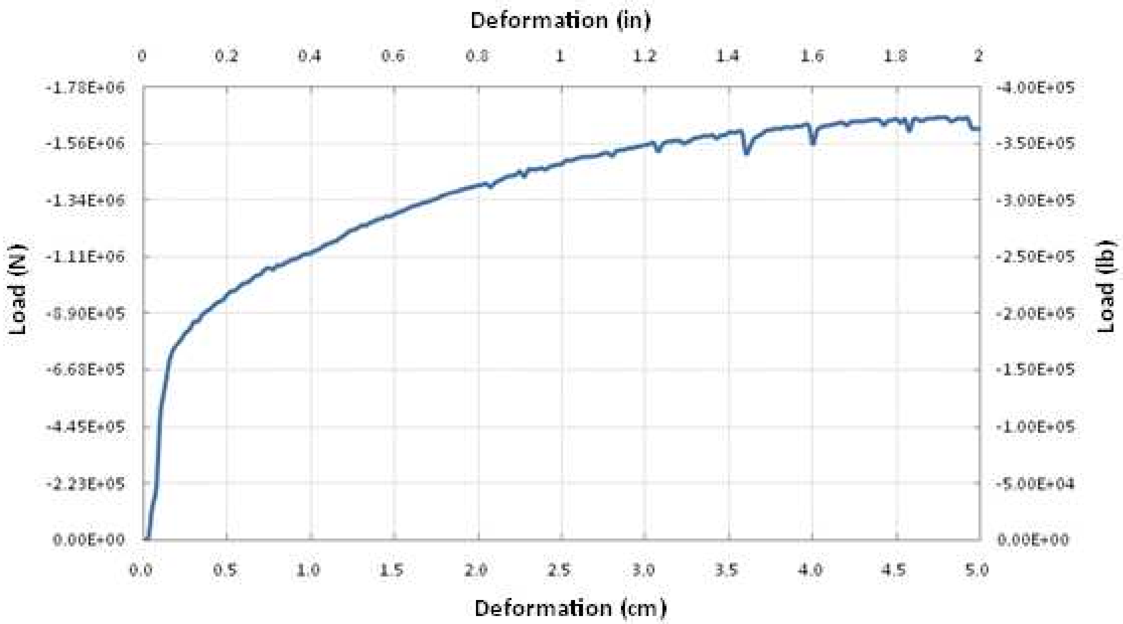


Fig. 44. Load-deformation relationship of the 1.27 cm (0.5 in) thick square stopper subjected to 5.08 cm (2 in) deformation.

Analysis for the second type of stopper focuses on the tapered stoppers. The tapered stopper has inconsistent thickness along its web. Center and lower portion of the web is thicker than tapered zone to provide more stiffness and enhance stability of the stopper when subjecting to a lateral load. In this study, the tapered stopper is simulated to evaluate its pounding performance and compare the result with previous type. Thickness of the pounding zone of the web is 1.27 cm (0.5 in) and of reinforced part is 5.08 cm (2 in) (Fig. 45). Fig. 46 shows the tapered stopper after pounding, and its load-deformation curve is shown in Fig. 47.

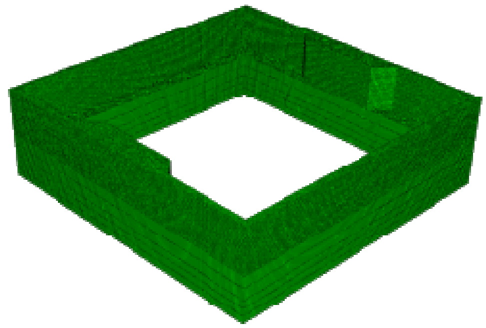


Fig. 45. Tapered stopper with 1.27 cm (0.5 in) thick pounding zone and 5.08 cm (2 in) thick reinforced part.

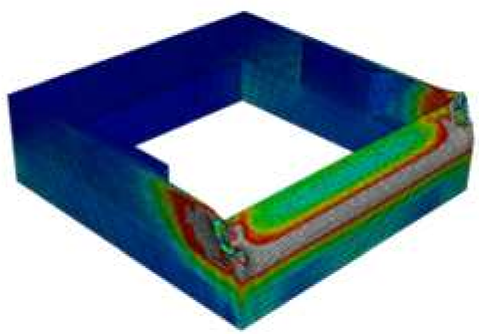


Fig. 46. Stress contour of the tapered stopper subjected to 5.08 cm (2 in) deformation.

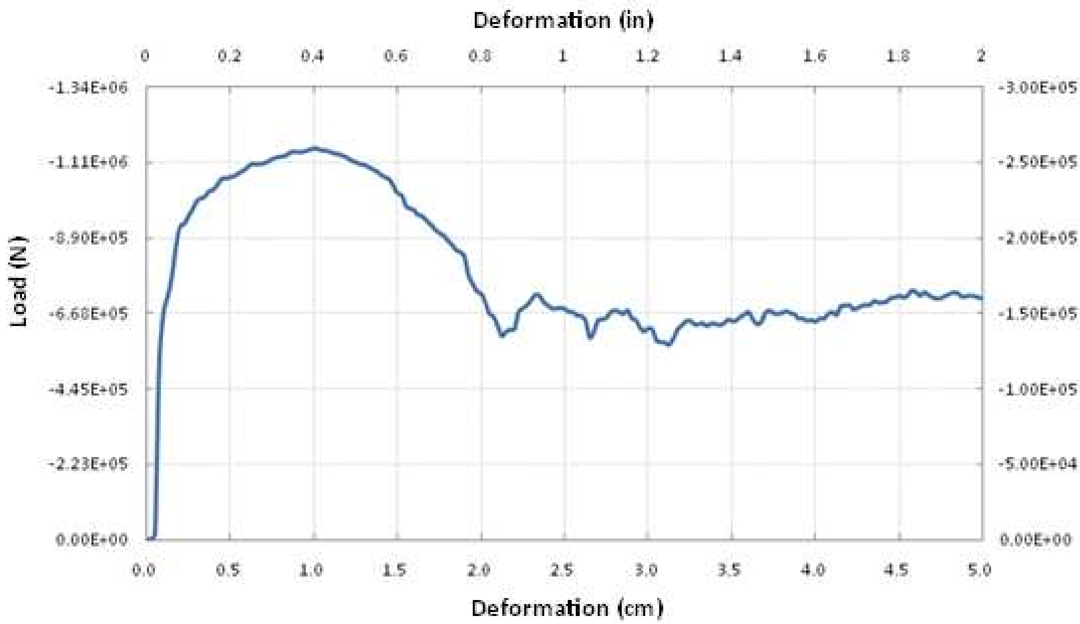


Fig. 47. Load-deformation relationship of the tapered stopper subjected to 5.08 cm (2 in) deformation.

From the result of this simulation, the initial portion of the curve in Fig. 47 is similar to the result of a square stopper with 1.27 cm (0.5 in) thickness as shown in Fig. 44. However, after a 1.02 cm (0.4 in) deformation, a significant drop of stiffness is observed in the curve because of damage at the corner of tapered stopper as shown in Fig. 48. The tapered stopper's rigidity is largely increased by increasing the thickness of the middle part of the webs. The stopper becomes less flexible, and major deformation is limited in the tapered zone. Connection of two plates increases rigidity at the corner area and decreases it ductility. With this large local deformation, the corners of stopper tend to failure, and the stiffness of stopper will decrease obviously. The lack of integrity causes another instability issue of the stopper. To mitigate this problem, a stiffened stopper is introduced. Two pieces of interior stiffeners are applied in each direction to provide reliable resistance.

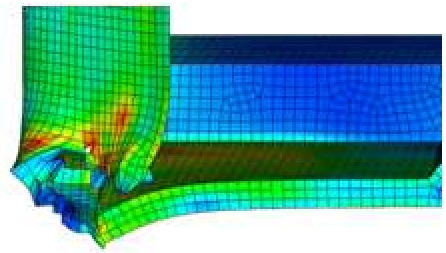


Fig. 48. Failure at the corner of the stopper.

The third type focuses on the stiffened stopper, which consists of a square stopper and two pieces of flexible interior stiffeners in each direction as shown in Fig. 49. The additional two pieces of stiffener can provide reliable resistance after failure of corners and enhance stability. In general, the stopper is design to limit deck movement in both longitudinal and transverse direction, and interior stiffeners help to maintain its reliability during continuous pounding from different directions. First pounding from the longitudinal direction will cause the contact zone to yield and thus decrease capability of this web to resist the pounding force from the transverse direction. However, interior stiffeners in the middle area for resisting transverse force are not damaged by this longitudinal pounding, so they still can provide lateral resistance to resist force from transverse direction.

Thickness of the interior stiffeners should be determined according to expected performance. In general, transverse movement of deck is not desirable. In this condition, transverse interior stiffeners will be designed stronger than those in the longitudinal direction to avoid large deformation, and the gap between stopper and deck component would be small. To maintain stability and integrity of stopper under pounding force and avoid large distortion, lower portion of stiffened stopper designed thicker than upper portion to serve as a solid base.

A study of a stiffened stopper with 0.635 cm-thick (0.25 in) webs and 0.635 cm-thick (0.25 in) stiffener plates is presented in Fig. 49. In this case, under a 5 cm (2 in) deformation, the contact area is serious damaged (Fig. 50), but it can be shown in the stress contour (Fig. 51) that the interior stiffeners in transverse direction are still in elastic range. Therefore, it reserves its most of ability to resist pounding force in the other direction. The load-deformation curve shown in Fig. 52 indicates that the stiffness of stopper keeps increasing when deformation reaches 1.02 cm (0.4 in) and decrease significantly when deformation reaches 3.6 cm (1.4 in). This result indicates that a stiffened stopper is more ductile than a stopper without interior stiffeners.

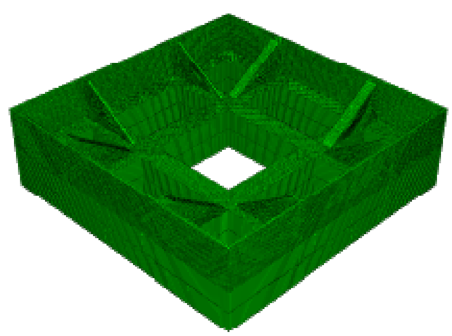


Fig. 49. Stiffened stopper.

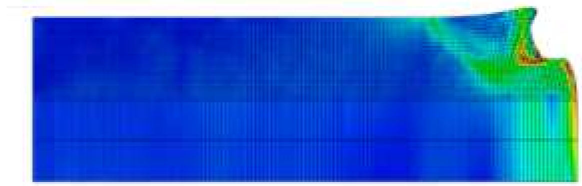


Fig. 50. Side view of the stress contour of the stiffened stopper subjected to 5.08 cm (2 in) deformation.

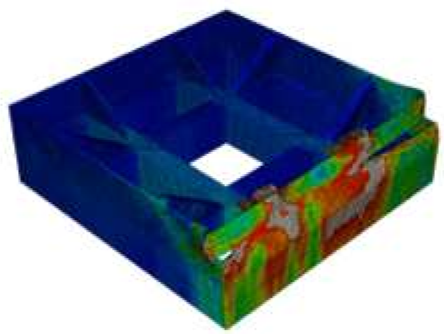


Fig. 51. Stress contour of the stiffened stopper subjected to 5.08 cm (2 in) deformation.

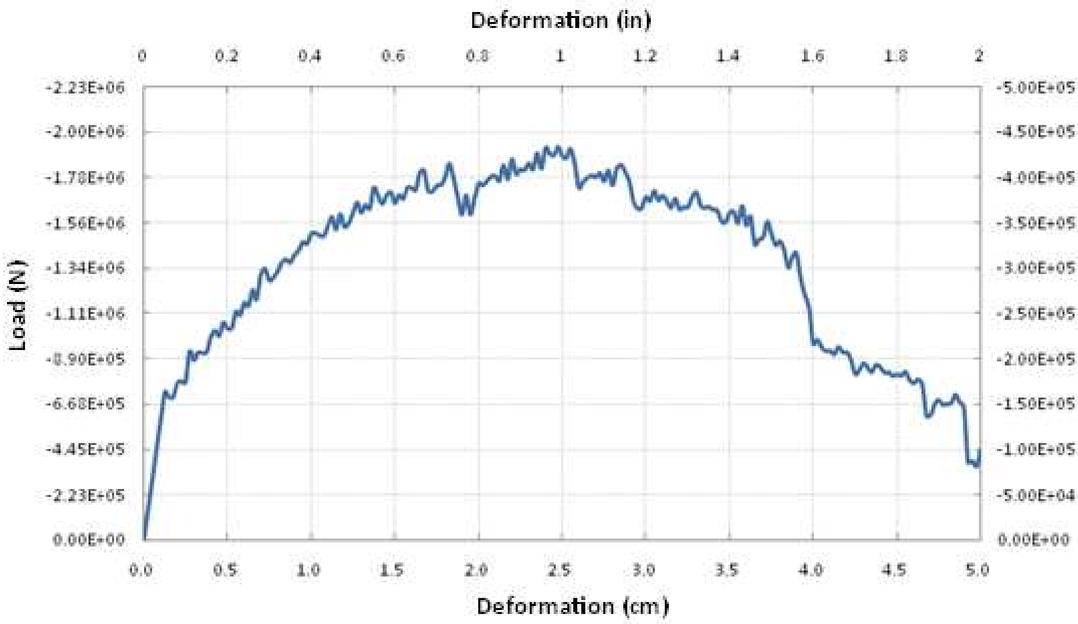


Fig. 52. Load-deformation relationship of the stiffened stopper subjected to 5.08 cm (2 in) deformation.

As such, there are six stoppers with different sizes of webs and interior stiffeners investigated in ABAQUS to determine the capacities. Layout of these stoppers and their corresponding maximum force capacities are listed in Table 4. The locations of A, B, and C can be found in Fig. 53. Parameter A represents thickness of the web contacting deck component. Parameter B represents thickness of the web along to the direction of deck movement, and parameter C represents thickness of the interior stiffeners along the direction of deck movement. Load-deformation relationship of these stoppers is shown in Fig. 54.

The results show that with the support of interior stiffeners, stoppers become more stable when applying thinner plates. Expected performance can be achieved by proper selection of webs and interior stiffeners.

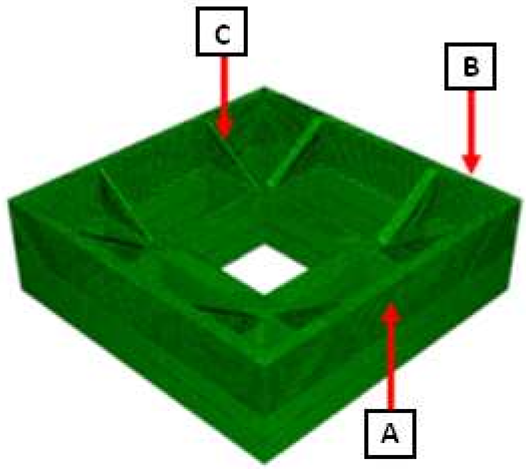


Fig. 53. Details of the stiffened stopper.

Table 4
Dimensions and capacities of stoppers.

Type	A (cm)	B (cm)	C (cm)	Capacity (kN)
1	2.54	2.54	2.54	7303
2	2.54	2.54	0.64	6008
3	2.54	0.64	0.64	4510
4	0.64	0.64	0.64	1927
5	0.64	0.51	0.25	977.7
6	0.64	0.25	0	770.8
7	0.25	0.25	0	226.8

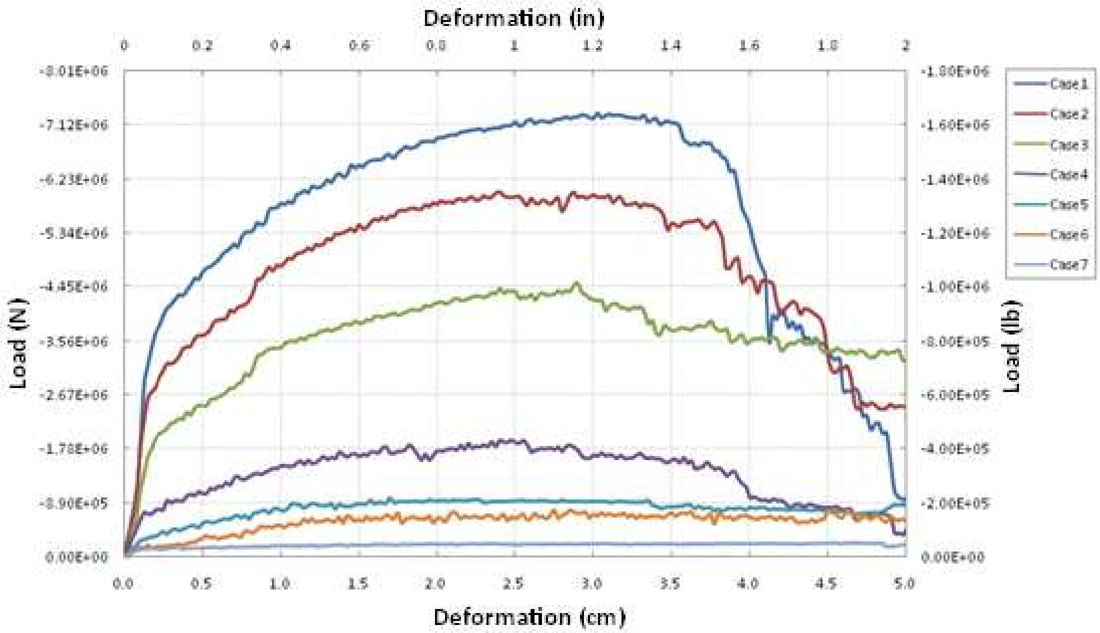


Fig. 54. Load-deformation relationships of various stiffened stoppers subjected to 5.08 cm (2 in) deformation.

4.2 Results from SAP2000

4.2.1 Selection of sizes of gaps for different bridge models

A gap is the distance between stopper and deck component and is the allowable distance for deck to move in designated directions. When deck movement reaches this value, gap closes and contact of stopper and deck component takes place. Gap is an important factor that can be controlled to achieve expected performance. In this research, two sets of ground motions (1.01g and 0.43g) are used, and the deck movement for a bridge model in these two events are different. The peak deck movements for the three 3D models are listed in Table 5. Note the deck movement in this research is the relative displacement between bridge deck and bent cap. According to Table 5, the gap sizes used in the 0.43g event are 2.54 cm (1 in) and 5.08 cm (2 in), and the gap used in the 1.01g event are 5.08 cm (2 in) and 10.16 cm (4 in). By applying these sizes of gap, pounding in the SBS will happen and influences generated by SBS can be obtained and studied.

Table 5
Maximum relative displacement between deck1 and left abutment for bridge models subjected to 0.43g and 1.01g ground motion.

	0.43g (Chi-Chi N-S)		1.01g (Chi-Chi E-W)	
Bridge Model	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
1 Span	4.5	4.7	18.0	17.6
2 Span	5.3	3.8	19.7	19.3
3 Span	5.9	3.7	20.1	19.3

4.2.2 Performance of bridge models equipped with SBS

4.2.2.1 One-span simply-supported bridge

One-span simply-supported bridge is the simplest bridge structure, which is a good example to show the performance of a bridge after installing SBS. In this study, a single span bridge model is tested under two sets of ground motions (1.01g and 0.43g) acting in the longitudinal direction. Time history data of deck movement and shear force in the left abutment are presented as examples.

For the case of a single-span simply-supported bridge model subjected to a 1.01g ground motion, Fig. 55 is the time history of deck movement for bridge without SBS. Fig. 56 and Fig. 57 are the time histories of deck movement for bridges equipped with

SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively. Fig. 58 and Fig. 59 are the load-deformation curves of the SBS with 5.08 cm (2 in) gap subjected to the 1.01g ground motion. The locations of these two SBS are shown in Fig. 60. Fig. 61 shows the time history of shear force in left abutment for bridge without SBS. Fig. 62 and Fig. 63 are the time histories of shear force in left abutment for bridges equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively. Maximum values of relative deck displacement and shear forces at selected locations are listed in Table 6, Table 7, Table 8 and Table 9. These values are summarized in Fig. 64, Fig. 65, Fig. 66 and Fig. 67.

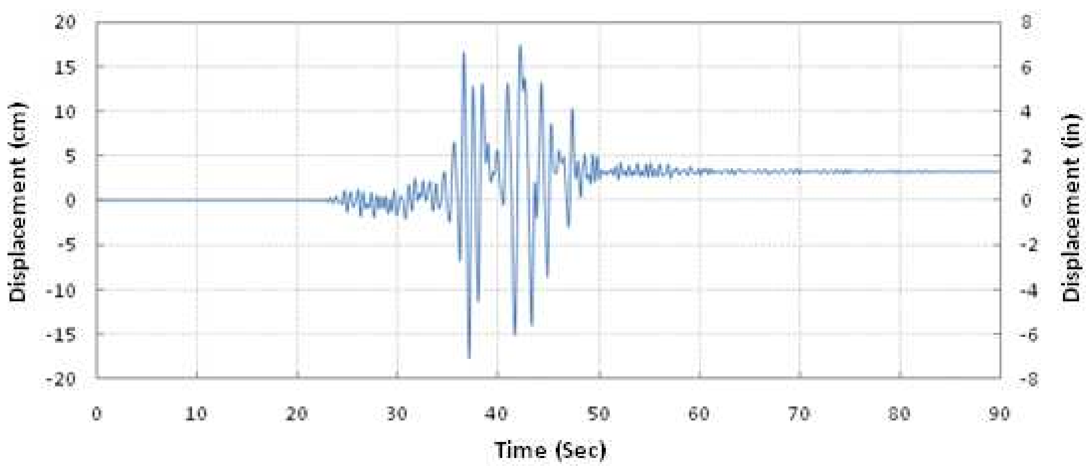


Fig. 55. Displacement of the deck in the bridge without SBS under a 1.01g ground motion.

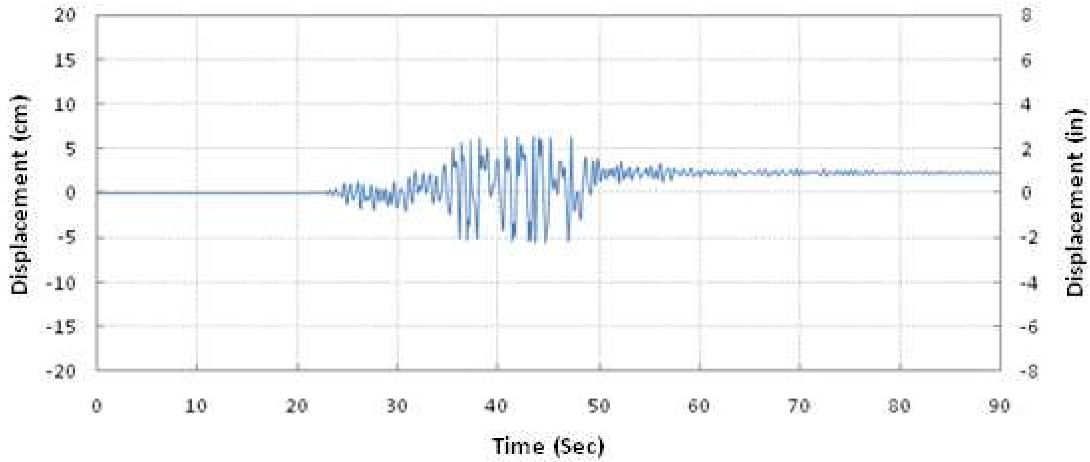


Fig. 56. Displacement of the deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

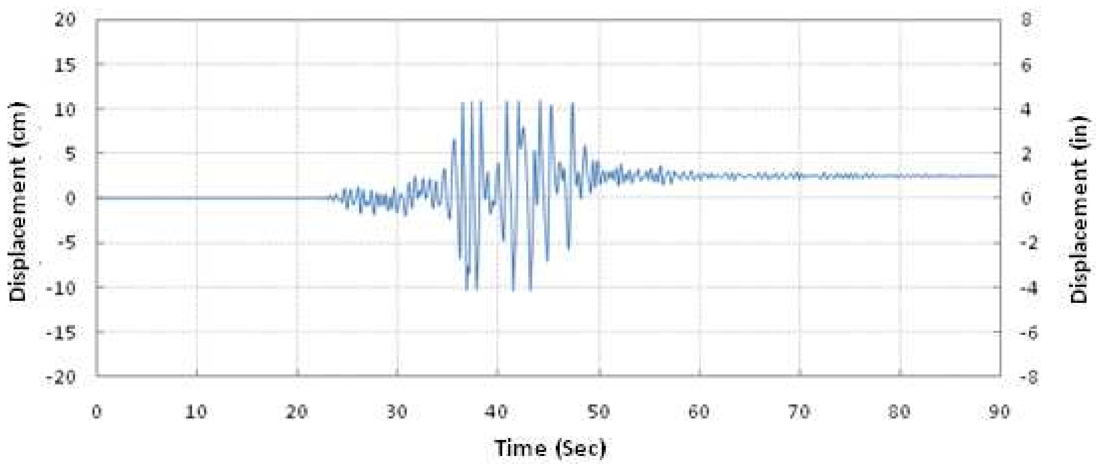
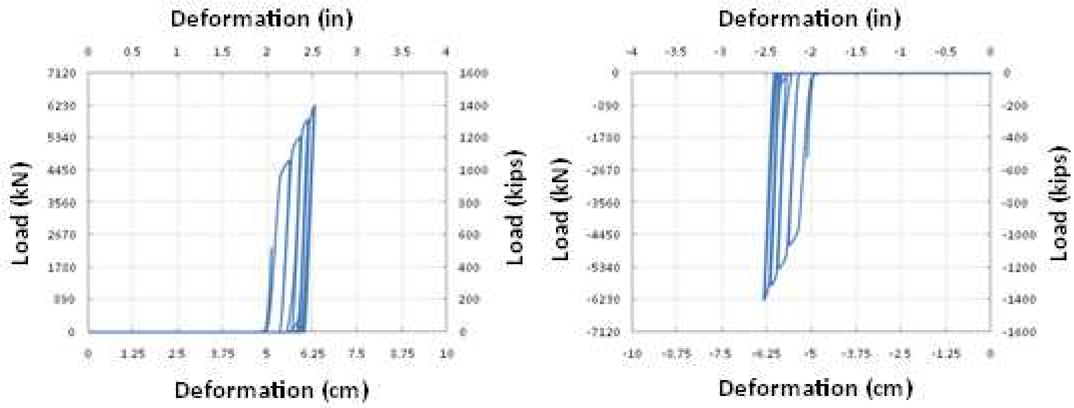
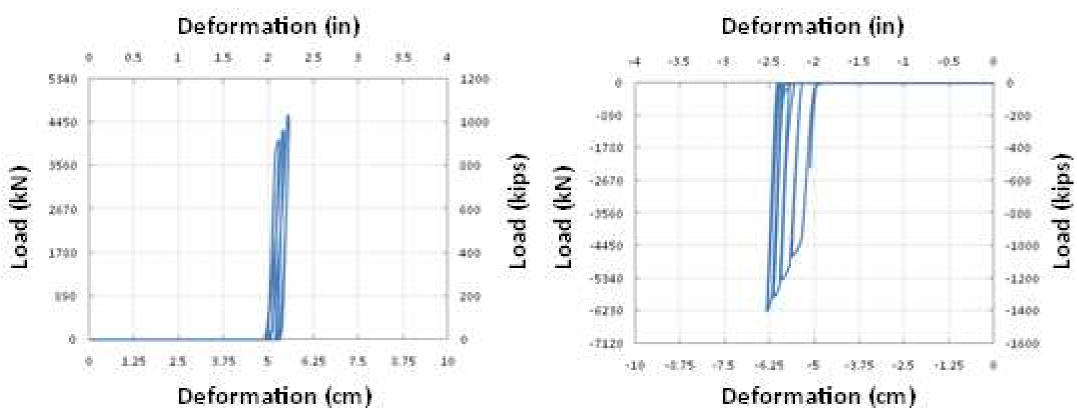


Fig. 57. Displacement of the deck in the bridge equipped with SBS (tupe1, 10.16 cm (4 in) gap) under a 1.01g ground motion.



(a) (b)

Fig. 58. Load-deformation relationship of the SBS (type1, 5.08 cm (2 in) gap) at the left end of the deck under a 1.01g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.



(a) (b)

Fig. 59. Load-deformation relationship of the SBS (type1, 5.08 cm (2 in) gap) at the right end of the deck under a 1.01g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

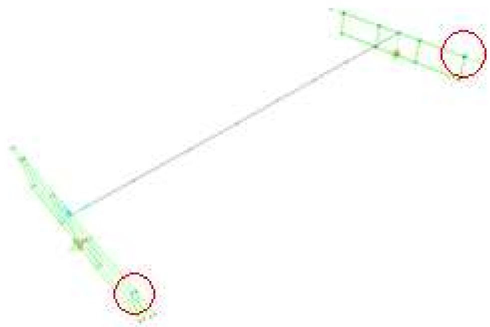


Fig. 60. Locations of the SBS in the bridge model.

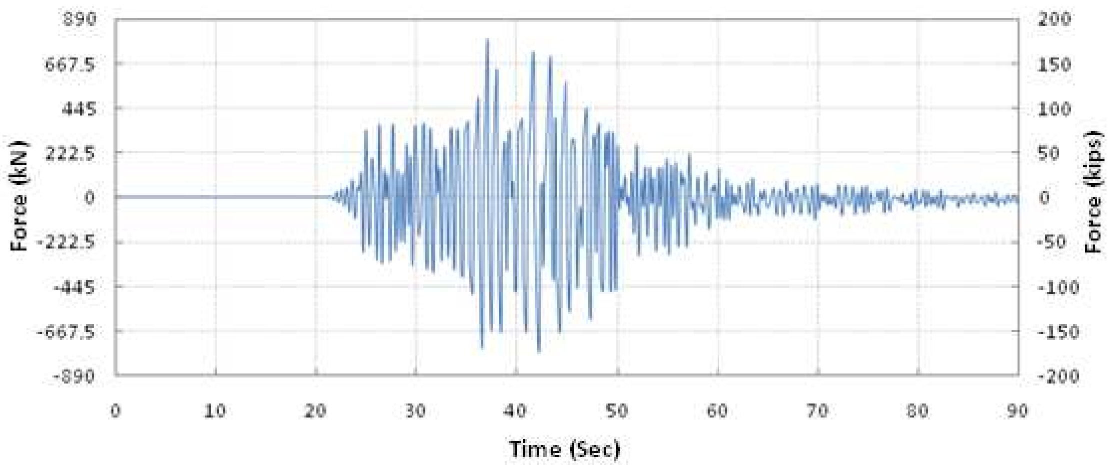


Fig. 61. Shear force in the left abutment in the bridge without SBS under a 1.01g ground motion.

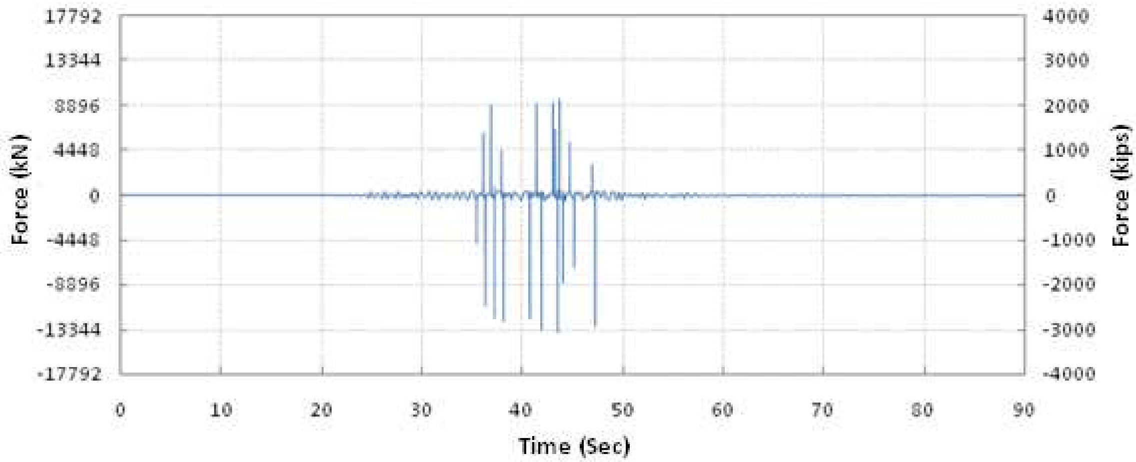


Fig. 62. Shear force in the left abutment in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

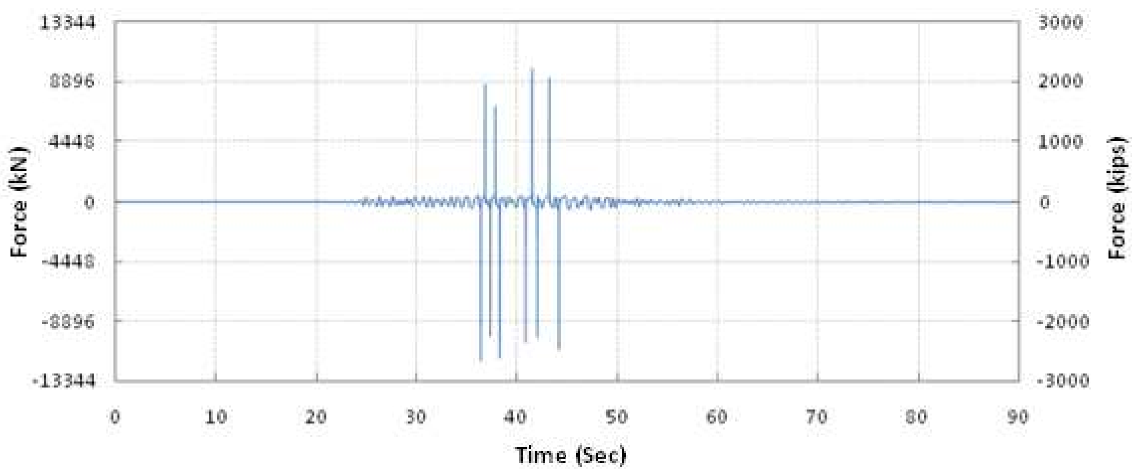


Fig. 63. Shear force in the left abutment in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.

Table 6
Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	18.0	17.6	17.6	18.0
1	6.4	5.7	5.7	6.4
3	7.1	5.8	5.8	7.1
5	9.3	13.2	13.2	9.3
6	11.1	13.6	13.6	11.1

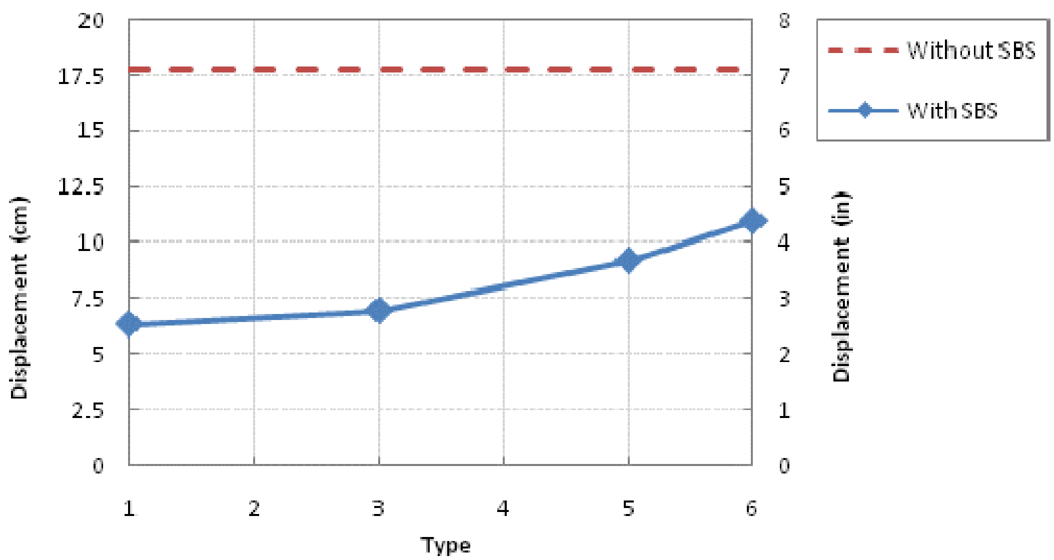


Fig. 64. Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

Table 7
Shear force at the abutments (left and right) in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

	Left Abutment		Right Abutment	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	786.0	-777.1	786.0	-777.1
1	9536.5	-13597.5	9518.7	-13557.5
3	6640.9	-9127.3	6645.3	-9100.6
5	2491.8	-2411.3	2481.5	-2406.4
6	1931.8	-1876.6	1929.1	-1874.8

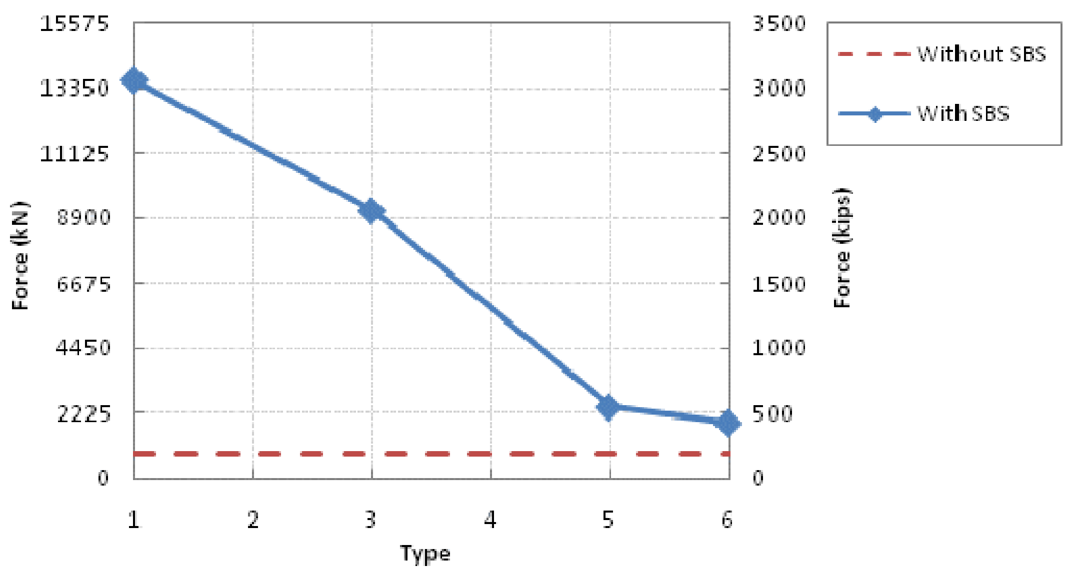


Fig. 65. Maximum shear force in the left abutment in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

Table 8
Relative displacement of the deck in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

	Deck1 Left Edge		Deck1 Right Edge	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	18.0	17.6	17.6	18.0
1	10.6	11.0	11.0	10.6
3	10.9	11.4	11.4	10.9
5	14.4	15.8	15.8	14.4
6	14.6	16.6	16.6	14.6

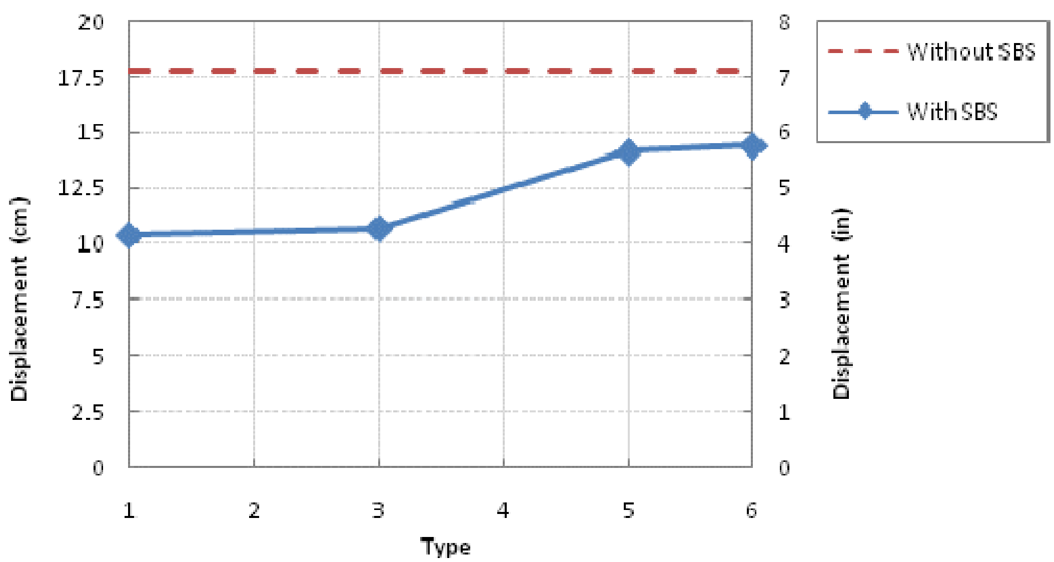


Fig. 66. Relative displacement of the deck in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

Table 9
Shear force at the abutments (left and right) in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

	Left Abutment		Right Abutment	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	786.0	-777.1	786.0	-777.1
1	9874.6	-11782.8	9843.4	-11671.6
3	7001.2	-8171.0	6974.5	-8144.3
5	2598.1	-2538.5	2589.2	-2533.1
6	2045.2	-2021.2	2043.4	-2021.2

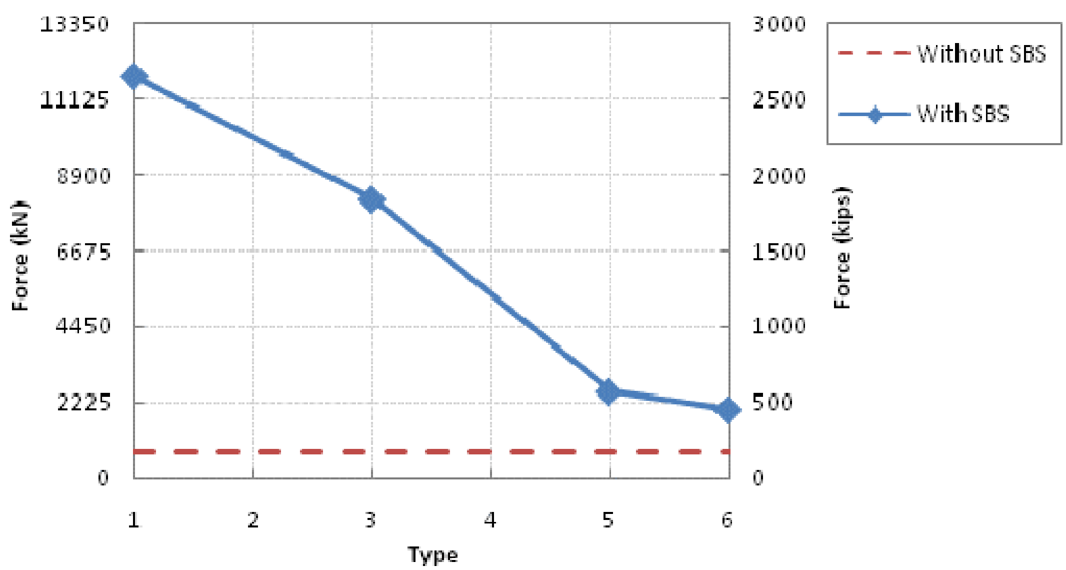


Fig. 67. Maximum shear force in the left abutment in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

For the case of a one-span simply-supported bridge model subjected to a 0.43g ground motion, Fig. 68 is the time history of deck movement for bridge without SBS. Fig. 69 and Fig. 70 are the time histories for bridges equipped with SBS (type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively. Fig. 71 and Fig. 72 are the load-deformation curves of the SBS with 1.27 cm (1 in) gap subjected to the 0.43g ground motion. The locations of the two SBS are the same as indicated in Fig. 60. Fig. 73 shows the time history of shear force in left abutment for bridge without SBS. Fig. 74 and Fig. 75 are time histories for bridges equipped with SBS (type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively. Maximum values of relative deck displacement and shear forces at all locations are listed in Table 10, Table 11, Table 12 and Table 13. These values are summarized in Fig. 76, Fig. 77, Fig. 78 and Fig. 79.

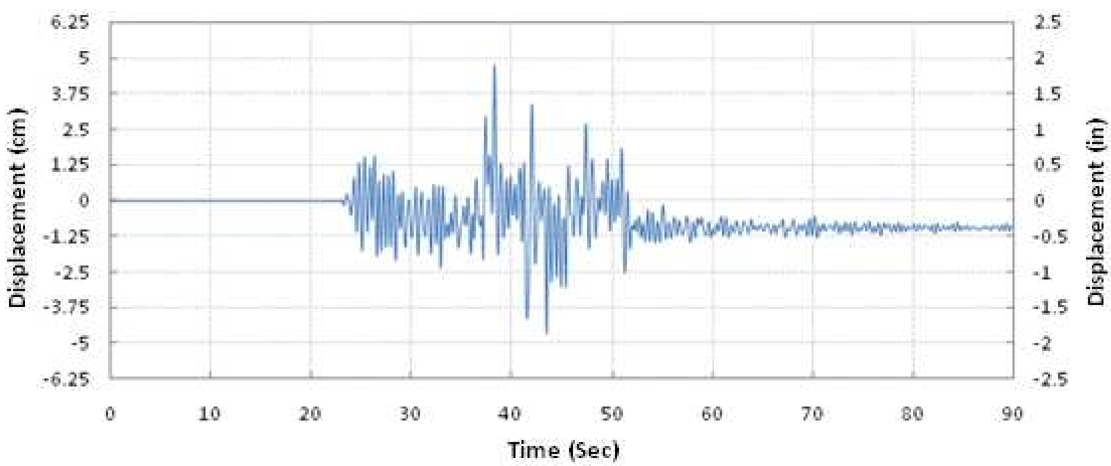


Fig. 68. Displacement of the deck in the bridge without SBS under a 0.43g ground motion.

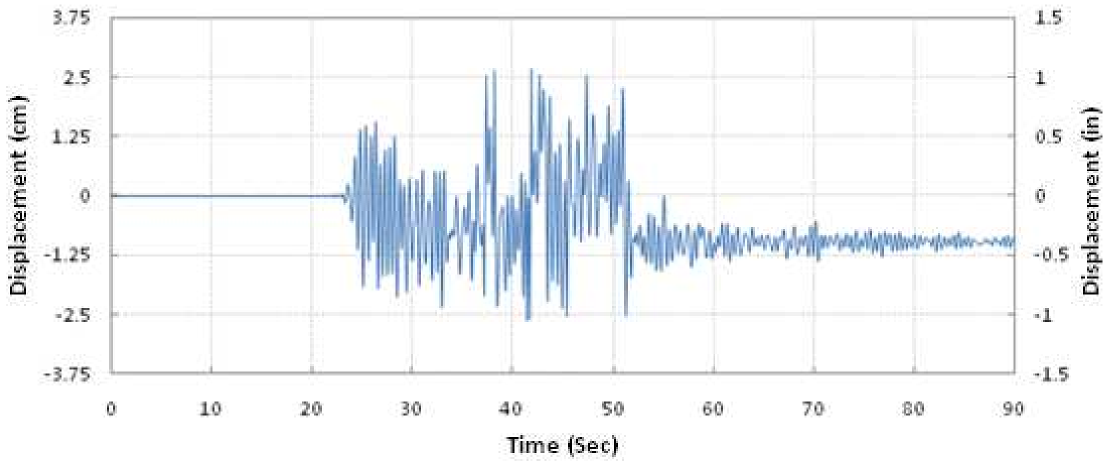


Fig. 69. Displacement of the deck in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

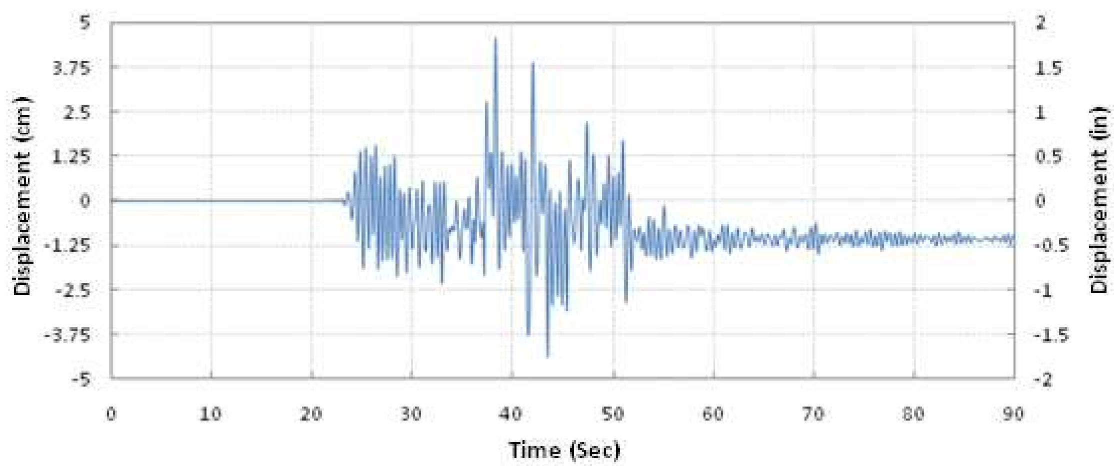
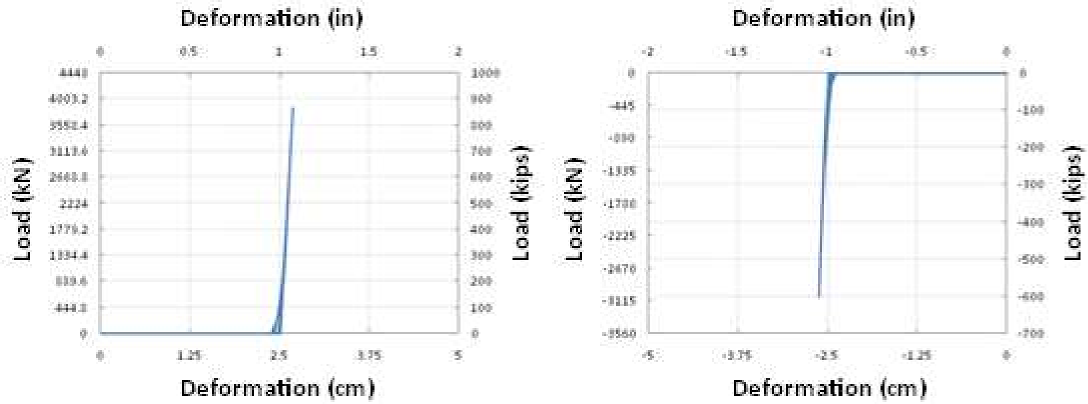
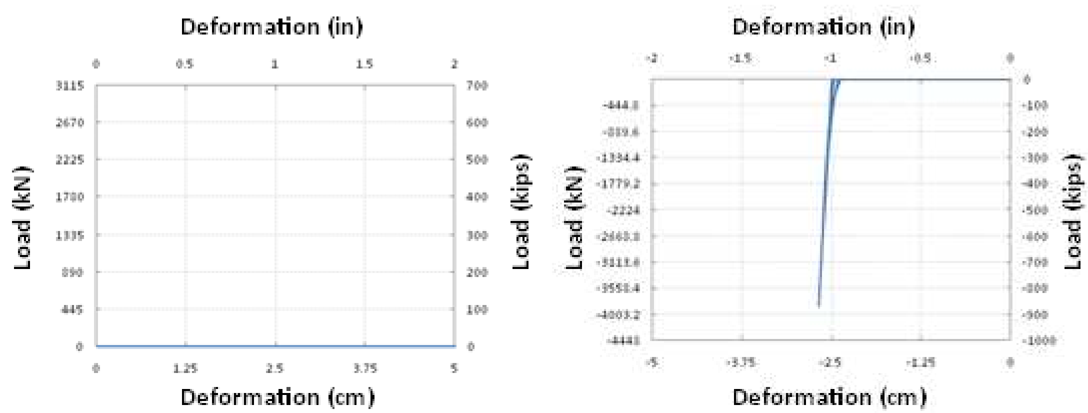


Fig. 70. Displacement of the deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.



(a) (b)

Fig. 71. Load-deformation relationship of the SBS (type1, 2.54 cm (1 in) gap) at the left end of the deck under a 0.43g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.



(a) (b)

Fig. 72. Load-deformation relationship of the SBS (type1, 2.54 cm (1 in) gap) at the right end of the deck under a 0.43g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

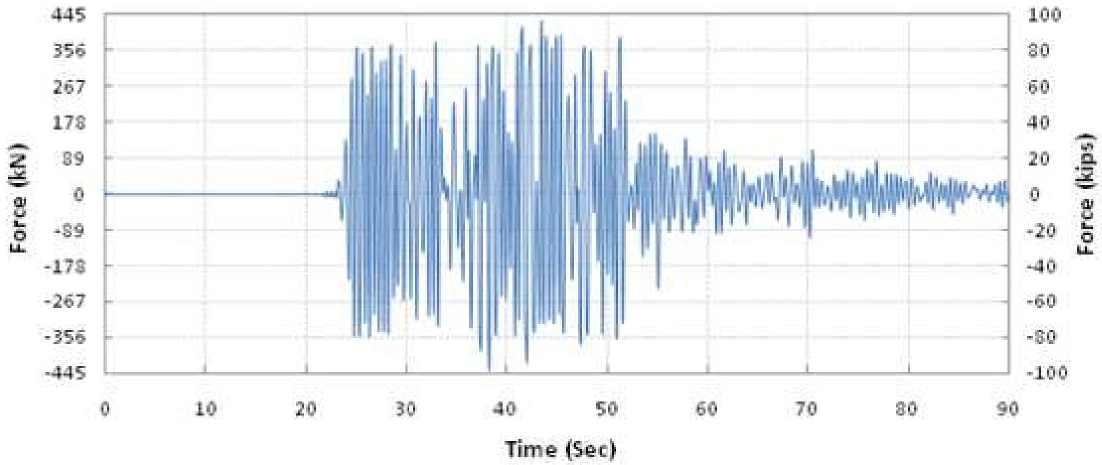


Fig. 73. Shear force in the left abutment in the bridge without SBS under a 0.43g ground motion.

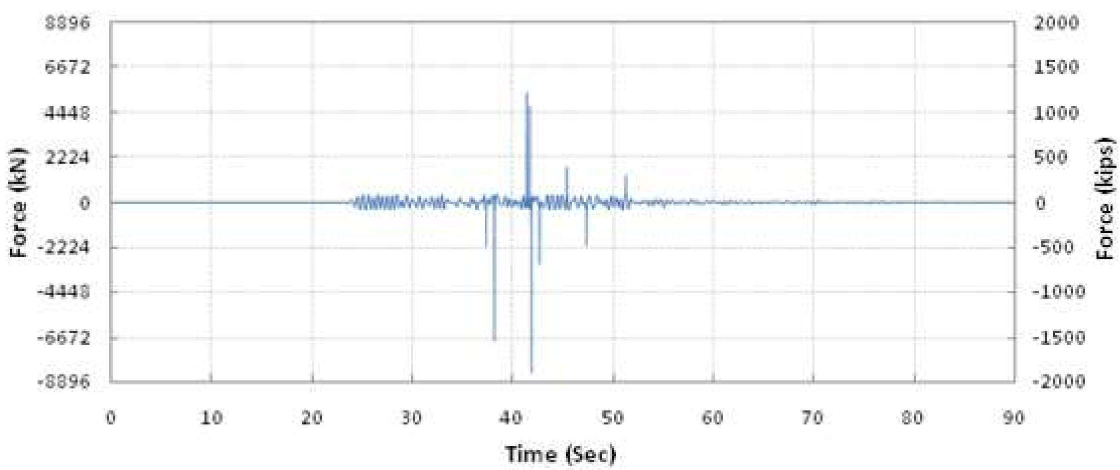


Fig. 74. Shear force in the left abutment in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

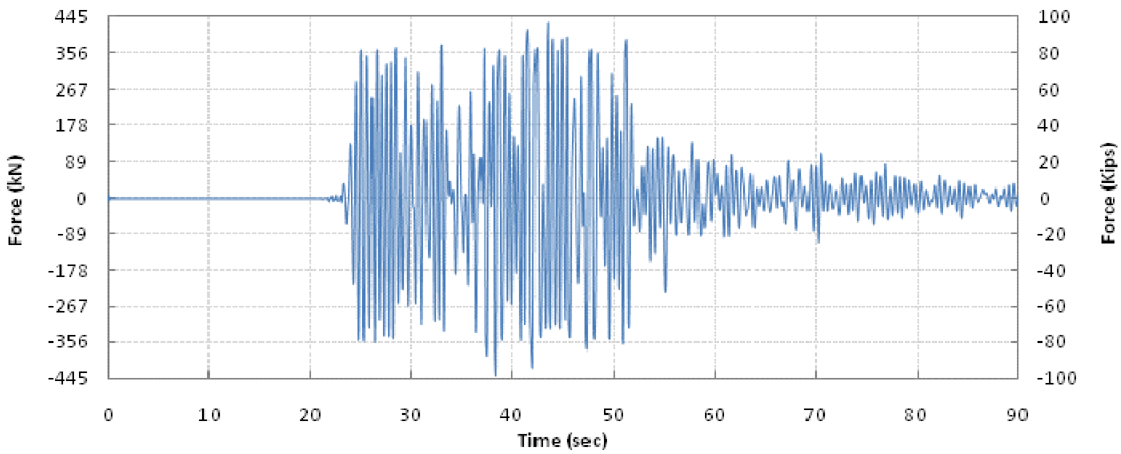


Fig. 75. Shear force in the left abutment in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.

Table 10
Relative displacement of the deck in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	4.5	4.7	4.7	4.5
1	2.7	2.7	2.7	2.7
3	2.7	2.9	2.9	2.7
5	3.5	3.2	3.2	3.5
6	3.7	3.5	3.5	3.7

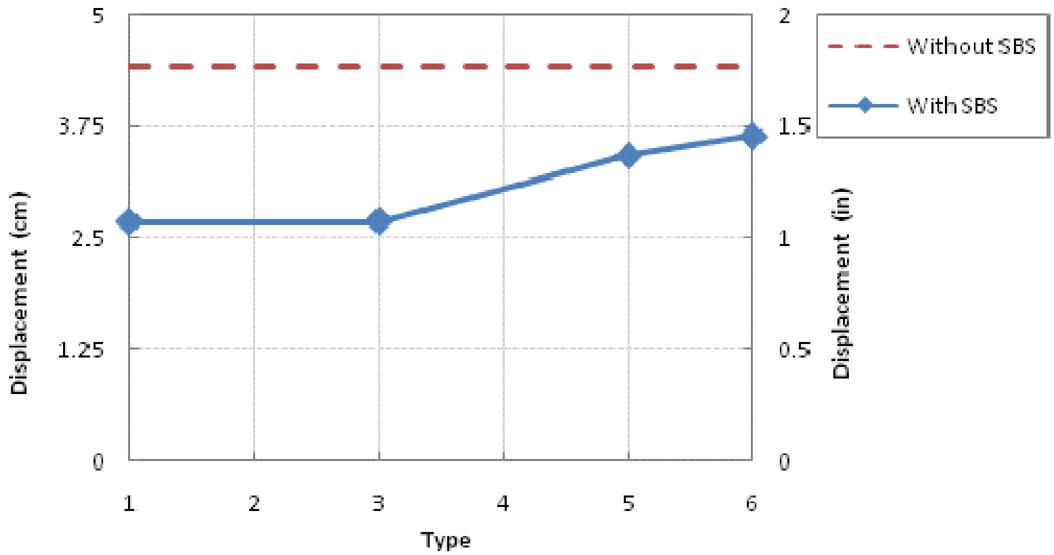


Fig. 76. Relative displacement of the deck in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

Table 11
Shear force at the abutments (left and right) in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

	Left Abutment		Right Abutment	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	430.7	-435.9	430.7	-435.9
1	5364.3	-8420.1	5386.5	-8402.3
3	4332.8	-5012.9	4323.5	-5004.0
5	1902.4	-1623.5	1901.5	-1623.1
6	1554.1	-1358.9	1554.1	-1359.3

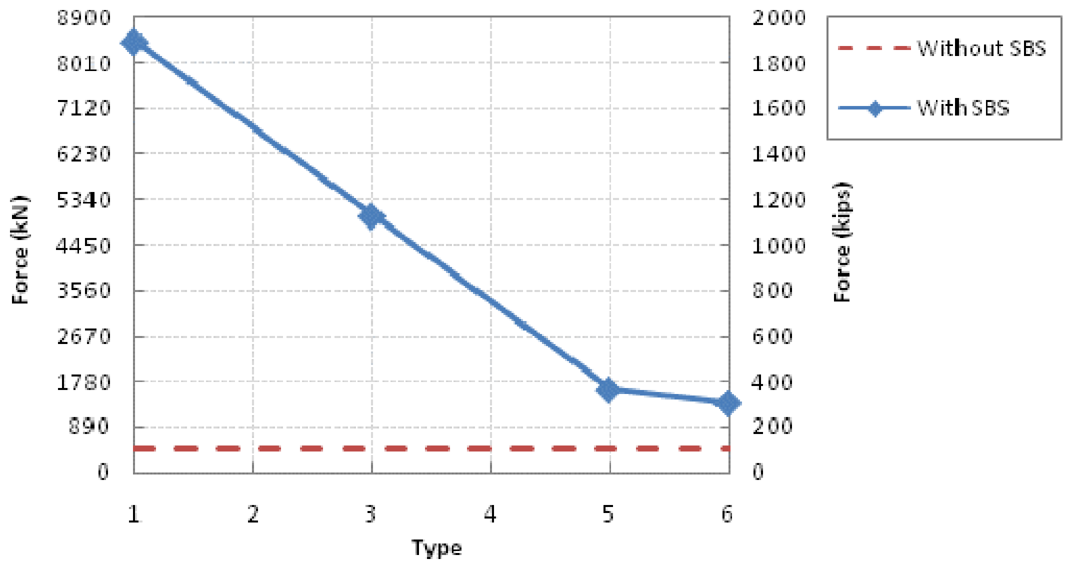


Fig. 77. Maximum shear force in the left abutment in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

Table 12
Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

	Left end of deck		Right end of deck	
SBS	Approach (cm)	Leave (cm)	Approach (cm)	Leave (cm)
w/o SBS	4.5	4.7	4.7	4.5
1	4.5	4.7	4.7	4.5
3	4.5	4.7	4.7	4.5
5	4.5	4.7	4.7	4.5
6	4.5	4.7	4.7	4.5

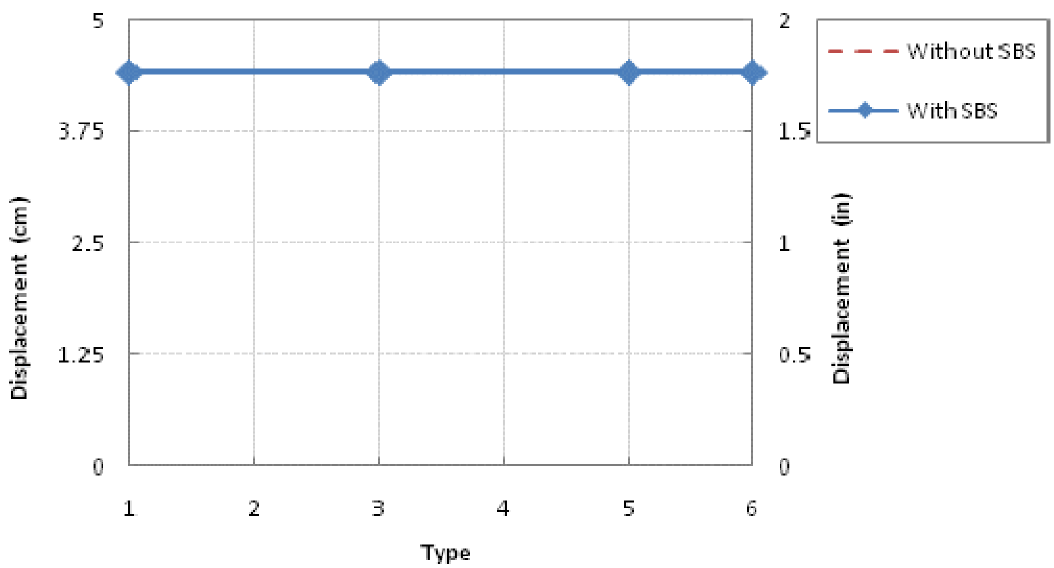


Fig. 78. Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

Table 13
Shear force at the abutments (left and right) in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

	Left Abutment		Right Abutment	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	430.7	-435.9	430.7	-435.9
1	430.7	-435.9	430.7	-435.9
3	430.7	-435.9	430.7	-435.9
5	430.7	-435.9	430.7	-435.9
6	430.7	-435.9	430.7	-435.9

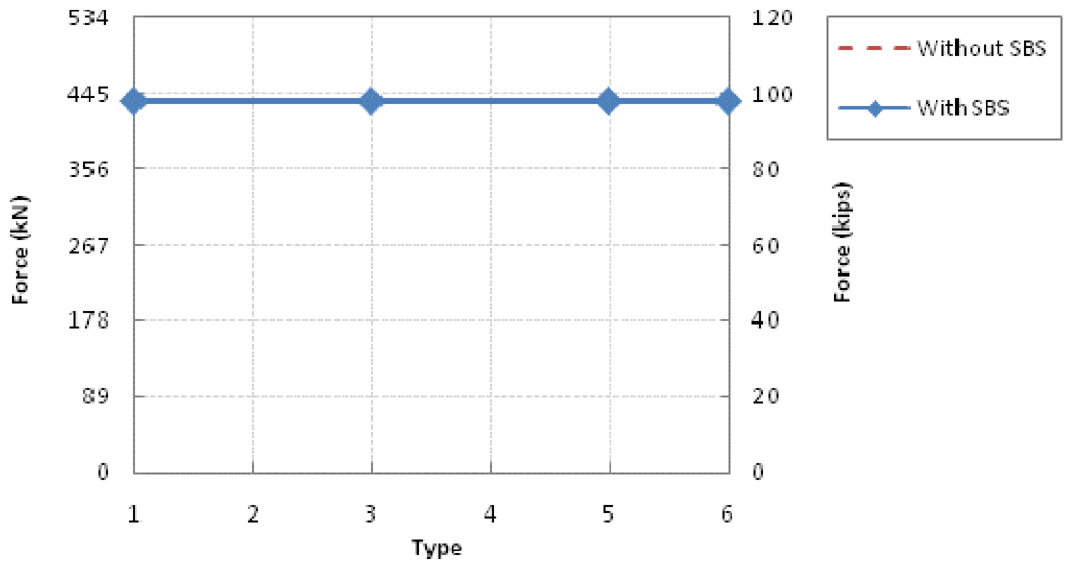


Fig. 79. Maximum shear force in the left abutment in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

From the analysis of case with 5.08 cm (2 in) gap under a 1.01g ground motion, the relative displacement between deck edge and abutment is limited by SBS. Effectiveness of various types of SBS is different depending on the resistance can be provided. Stopper type1 is the strongest with a resistance capacity of 7303 kN (1641.86 kips). It limits the deck movement from 18 cm (7.086 in) (without SBS) to 6.4 cm (2.528 in) with 5.08 cm (2 in) gap. Stopper type6 is the weakest with a resistance capacity of 770.8 kN (173.29 kips). It limits the deck movement from 18 cm (7.086 in) (without SBS) to 11.1 cm (4.381 in) with 5.08 cm (2 in) gap. In Fig. 64, Fig. 66 and Fig. 76, it is obvious that the performance of SBS depends on stopper's ability to resist lateral force. When the stopper is able to provide high lateral resistance, it can stop the deck immediately without large deformation. In this situation, the actual relative displacement between deck and bent cap will become closer to the design value, which is the width of gap. Since deformation will always happen in stopper after pounding, it is important to take the deformation into account when deciding the gaps. In Fig. 65 and Fig. 67, shear force transferred to substructure for each type of SBS has an opposite trend comparing to the trend for relative displacement as shown in Fig. 64 and Fig. 66. When stopper provides lateral resistance to stop the deck, same amount of shear force transferred down to substructure as well. Therefore, substructure has a chance to take higher shear force if stopper has higher capacity of lateral resistance. Similarly, stopper with lower capacity of lateral resistance will transfer less shear force to substructure.

The goal of SBS is to limit the displacement of deck in a desirable range, and a stronger stopper is more likely to achieve this expectation. However, from above analysis, applying a stronger stopper in the bridge will induce higher shear force in substructure under strong ground motion. The additional shear force transferred may exceed the capacity of substructure and cause damage. This is obviously not a favorable situation because the substructure is an important component of bridge and is related directly to integrity of the whole bridge system. To avoid this situation, proper selection of stopper is a viable way to obtain benefit from SBS and maintain healthiness of substructure at the same time.

The SBS can be applied to both new bridge construction and existing bridge. For a new construction, it is easier to take the additional shear force transferred by SBS into account when doing design. For an existing bridge, capacities of components are already determined. To achieve optimal performance provided by SBS, additional retrofitting may be encouraged and required. However, retrofitting a bridge requires budget and causes inconvenience to the public. Therefore, it is not always feasible to perform retrofitting on existing bridges. In this situation, SBS must be designed to lower its effectiveness to maintain the bridge in a good condition under strong ground motion.

Stopper plays a critical role in SBS for controlling the behavior of this system. It enables designers to determine the amount of additional shear force to be transferred to substructure via SBS. By careful stopper selection, it is possible to limit the total shear force transferred to substructure in a safe level. From previous analysis, it is obvious that when applying a stronger stopper, more extra shear force will be transferred down to substructure. To avoid damage caused by excessive shear force, designers may apply a stopper with less shear capacity. By making this change, less extra shear force will be transferred to substructure. However, the effectiveness of SBS to limit relative deck displacement is also decreased. This flexibility of stopper selection enables designer to apply SBS to bridges with various conditions. To achieve optimal performance and obtain maximum benefit from SBS, substructures with high capacity is required. Although such ideal condition may not be applicable in existing bridges, decreasing effectiveness of stopper still can provide certain protection to protect bridges under ground motion with low intensity.

Another way to keep low shear forces transferred to substructure without having large extra deck displacement is using different size of gaps. For this single-span bridge, if the favorable relative deck displacement is limited to 14 cm (5.5 in), the use of 5.08

cm (2 in) and 10.16 cm (4 in) gap make large difference for shear force. From Table 7 and Table 9, when using a 10.16 cm (4 in) gap, a Type3 stopper must be used to meet this requirement. The corresponding shear force transferred is 8171 kN (1837 kips). However, when using a 5.08 cm (2 in) gap, a Type6 stopper can meet this requirement, and the maximum shear force is 1931.8 kN (434.3 kips). Smaller gaps enables stopper to provide resistance and absorb energy gradually rather than stop the deck immediately. Therefore, larger deformation will be generated in a weaker stopper, but less lateral force will be transferred to the substructure.

4.2.2.2 Two-span simply-supported bridge

In this analysis, a two-span simply-supported bridge model is tested under two sets of ground motions (1.01g and 0.43g). Time history data of deck movement of the left deck and shear force in the left abutment are presented as examples.

For the case under a 1.01g ground motion, Fig.80 is the time history of deck movement of the left deck for the bridge without SBS. Fig. 81 and Fig. 82 are time histories of deck movement of the left deck for bridge models equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively. Fig. 83 and Fig. 84 are the load-deformation curves of the SBS with 5.08 cm (2 in) gap subjected to the 1.01g ground motion.

Fig. 85 shows the time history of shear force in left abutment for bridge without SBS. Fig. 86 and Fig. 87 are time histories of shear force in left abutment for bridges equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively.

Fig. 88 shows time history of shear force in central column of the column bent for bridge without SBS. Fig. 89 and Fig. 90 are time histories of shear force in the same column for bridges equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively.

Maximum values of relative deck displacement and shear forces at selected locations are listed in Table 14, Table 15, Table 16 and Table 17. These values are summarized in Fig. 91, Fig. 92, Fig. 93 and Fig. 94.

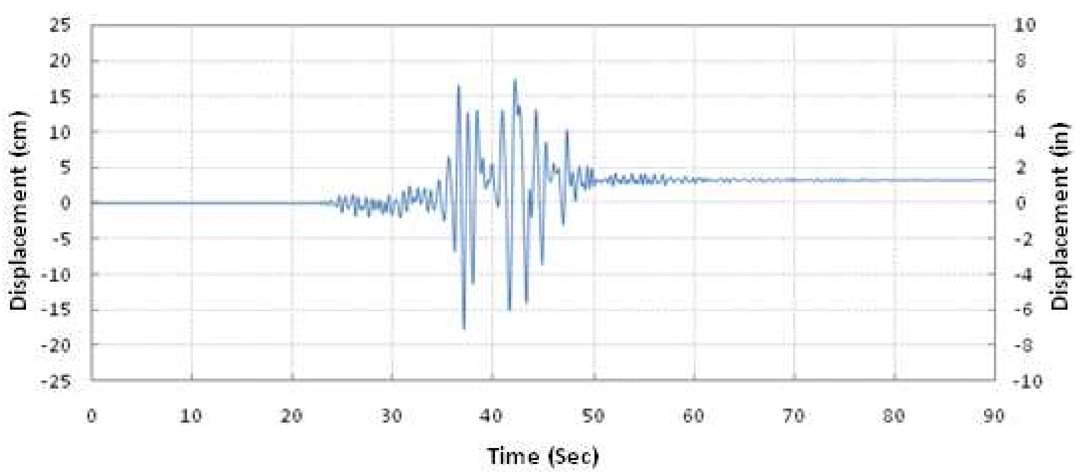


Fig. 80. Displacement of the left deck in the bridge without SBS under a 1.01g ground motion.

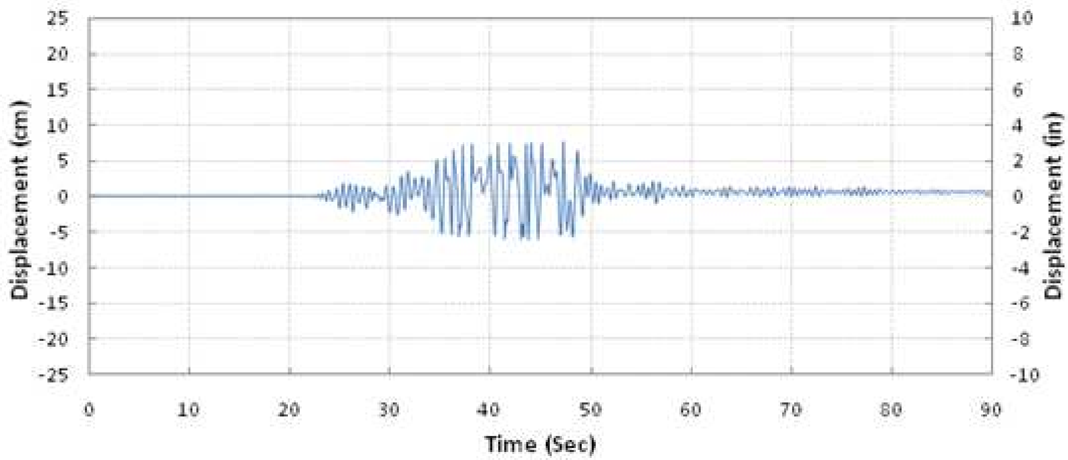


Fig. 81. Displacement of the left deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

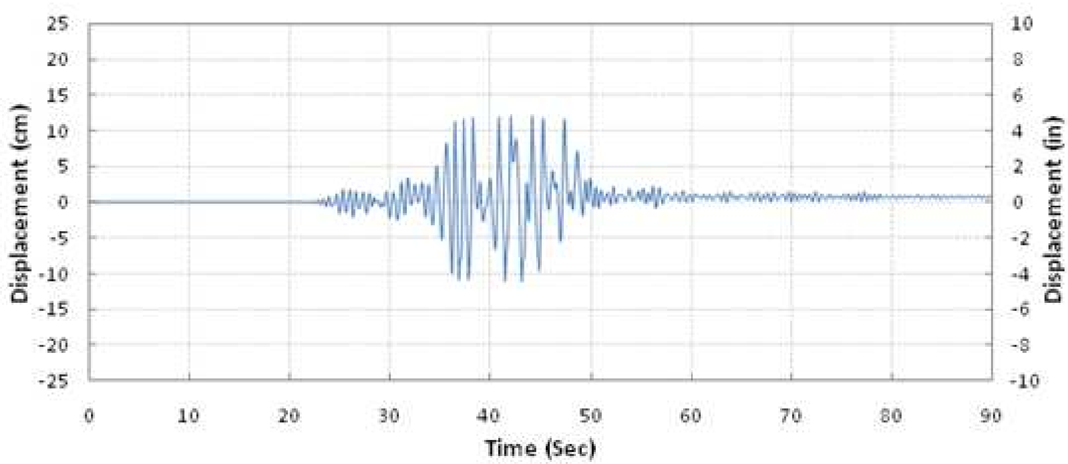
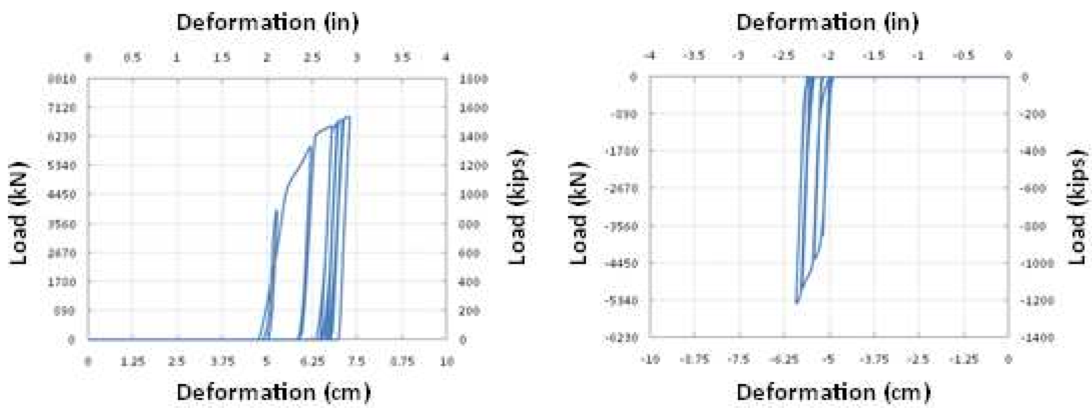
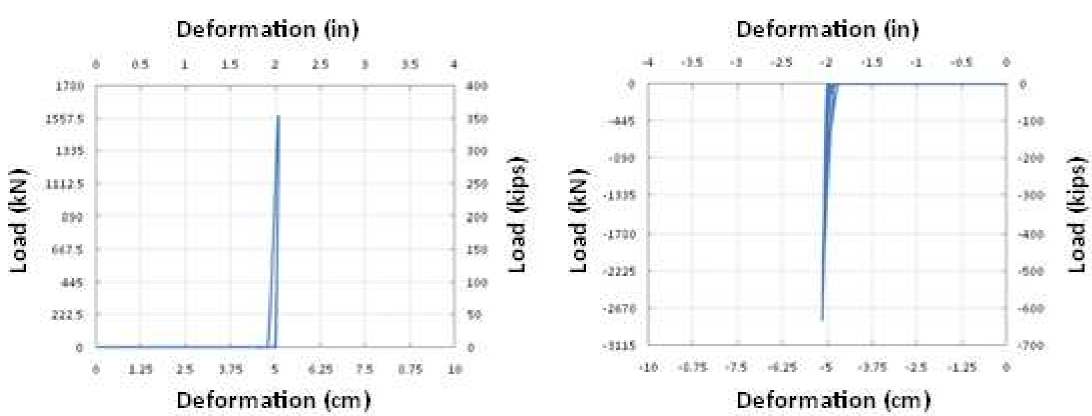


Fig. 82. Displacement of the left deck in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.



(a) (b)

Fig. 83. Load-deformation relationship of the SBS (type1, 5.08 cm (2 in) gap) at the left end of the deck under a 1.01g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.



(a) (b)

Fig. 84. Load-deformation relationship of the SBS (type1, 5.08 cm (2 in) gap) at the right end of the deck under a 1.01g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

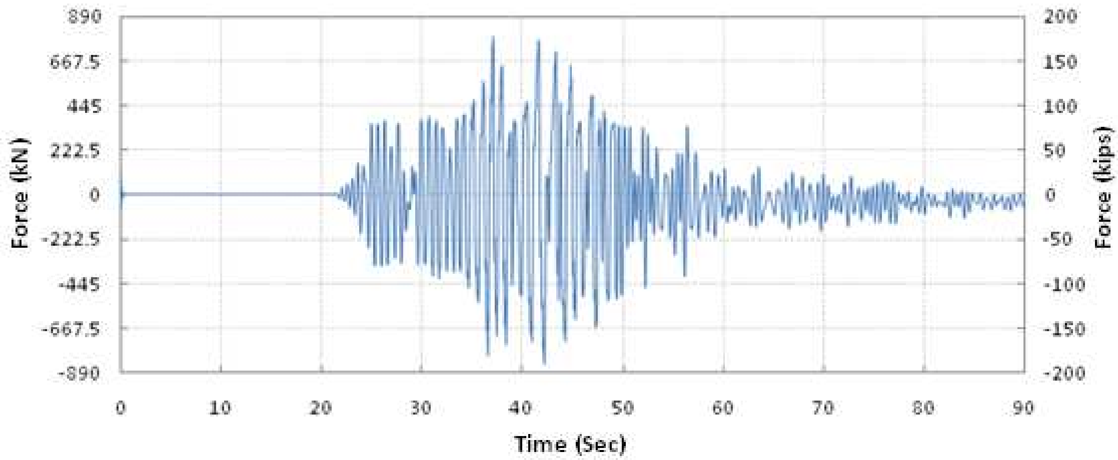


Fig. 85. Shear force in the left abutment in the bridge without SBS under a 1.01g ground motion.

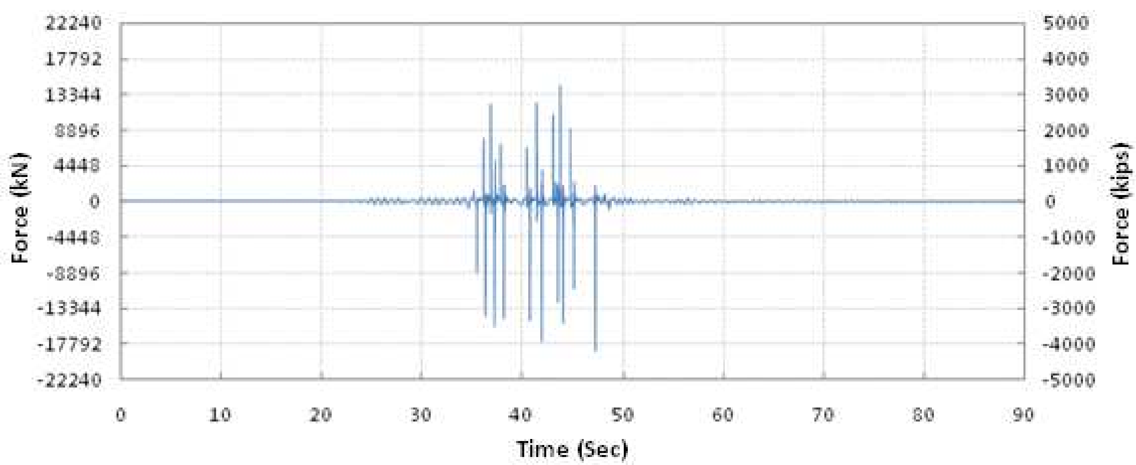


Fig. 86. Shear force in the left abutment in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

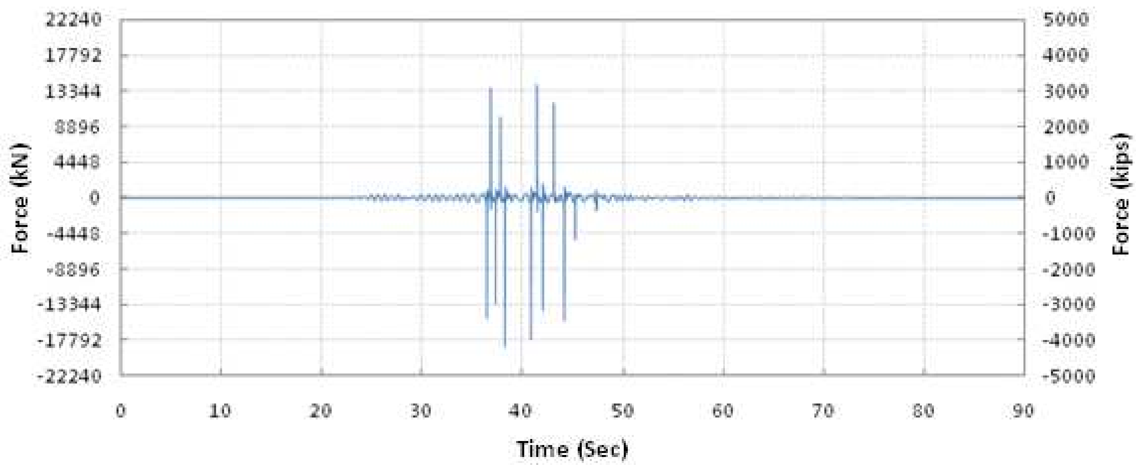


Fig. 87. Shear force in the left abutment in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.

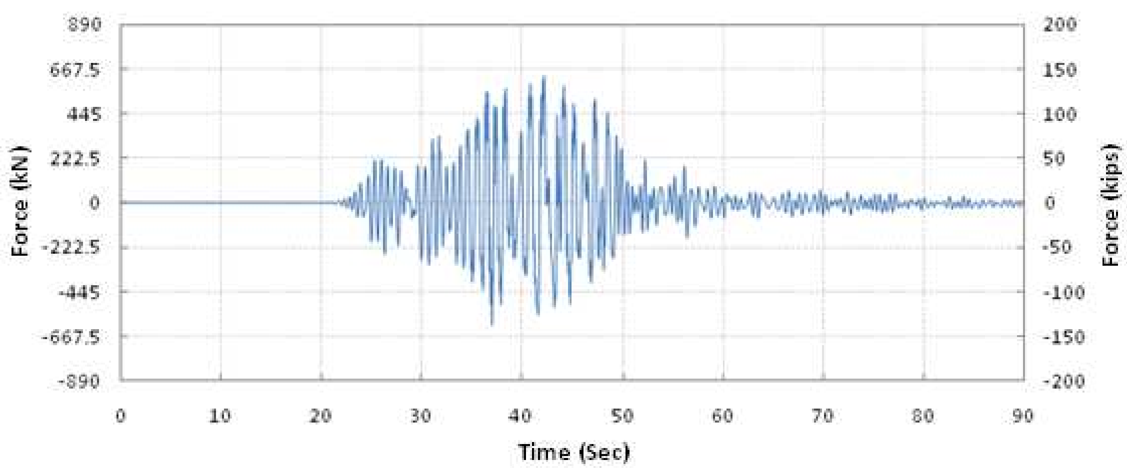


Fig. 88. Shear force in the central column of the bent in the bridge without SBS under a 1.01g ground motion.

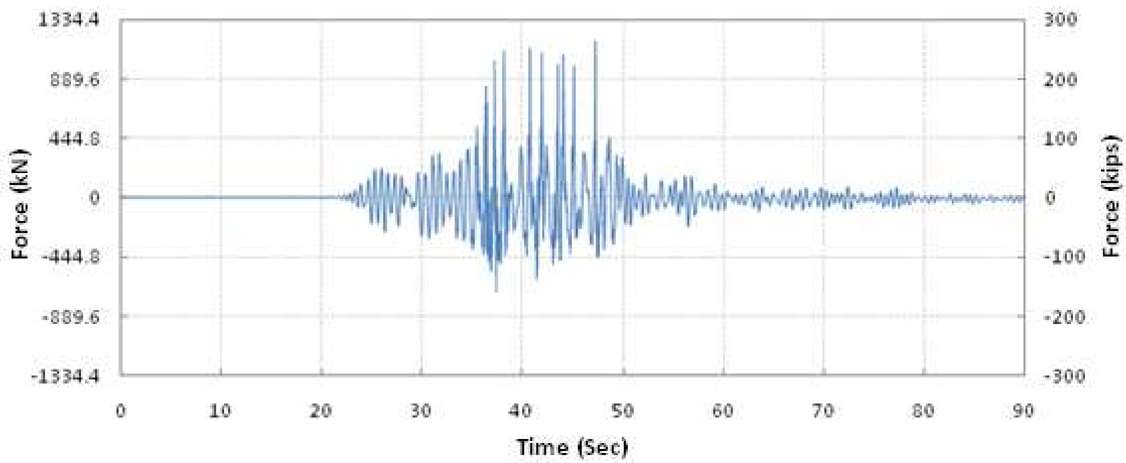


Fig. 89. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

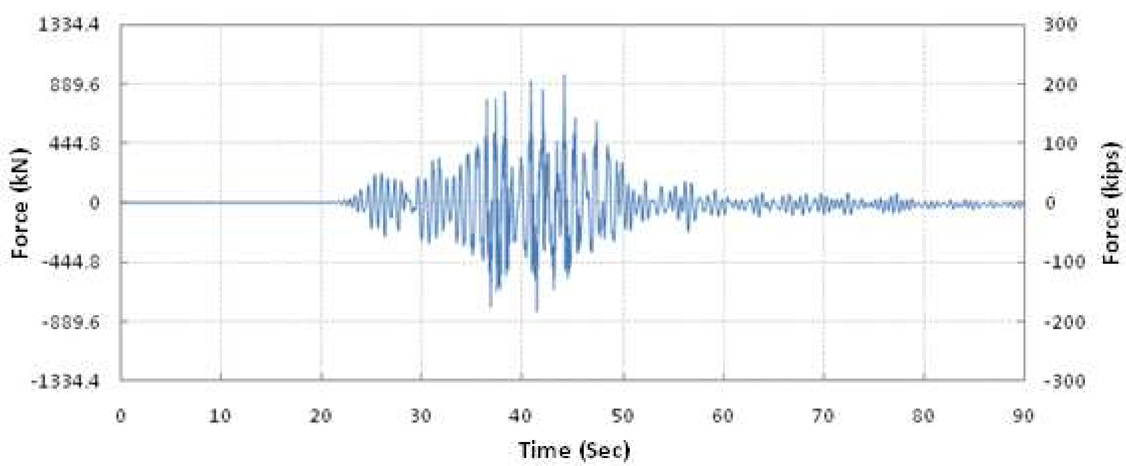


Fig. 90. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.

Table 14
Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	19.7	19.3	17.9	17.9
1	7.4	6.0	5.4	5.2
3	9.2	6.0	5.7	5.0
5	12.8	10.3	8.7	6.5
6	16.0	12.9	12.6	9.2

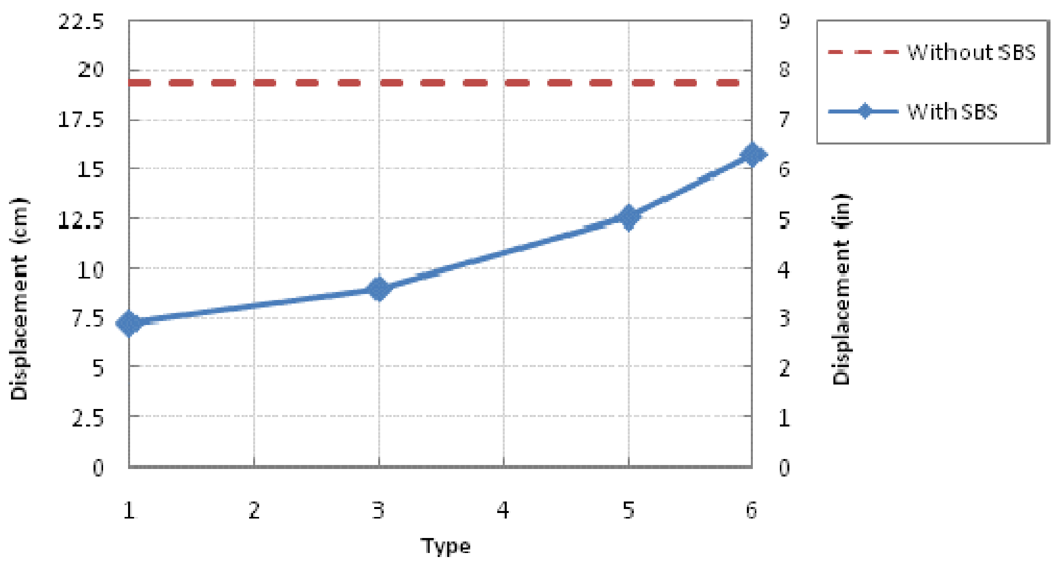


Fig. 91. Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

Table 15
Shear force in the left abutment and central column in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

	Left Abutment		Central Bent, Central Column	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	786.0	-850.5	633.4	-608.9
1	14309.2	-18543.7	1164.9	-703.7
3	7659.5	-11929.5	1504.8	-534.2
5	3087.4	-3200.3	1763.6	-1398.9
6	2349.9	-2733.3	1553.2	-1450.9

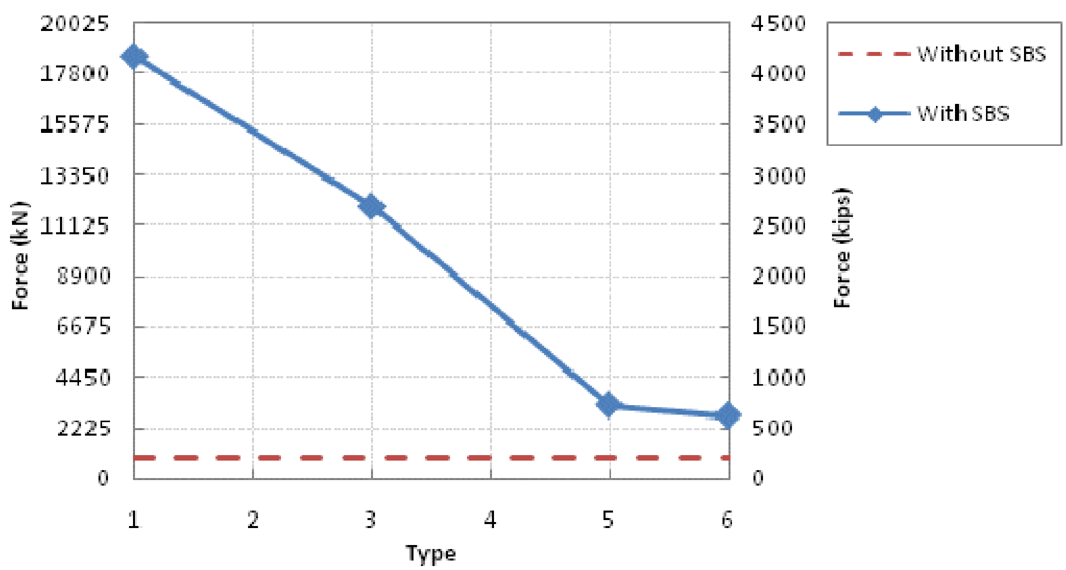


Fig. 92. Maximum shear force in the left abutment in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

Table 16
Relative displacement of the deck in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	19.7	19.3	17.9	17.9
1	12.0	11.2	10.4	9.9
3	12.7	11.7	10.7	10.3
5	18.3	16.3	13.4	11.7
6	20.0	16.2	16.4	12.5

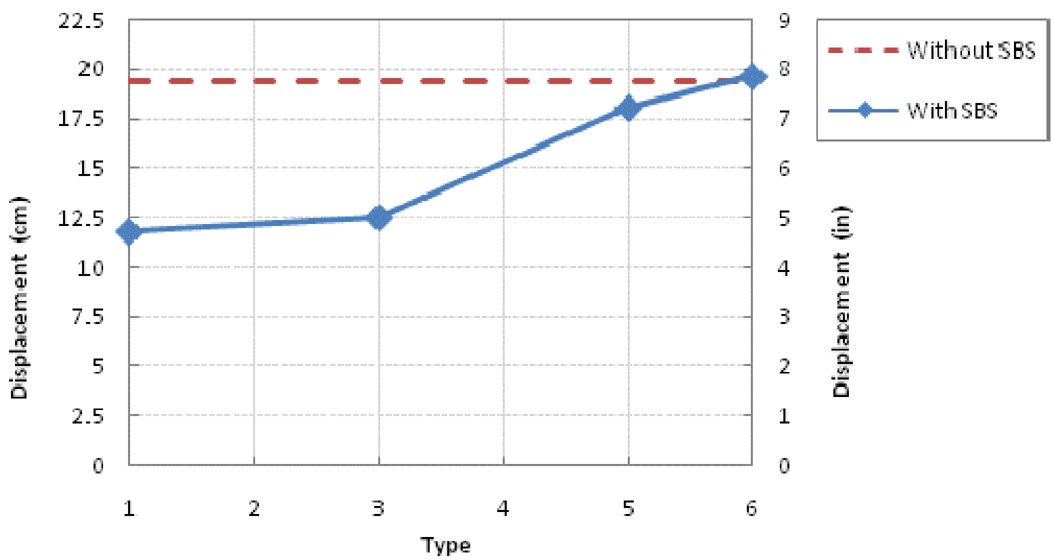


Fig. 93. Relative displacement of the deck in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

Table 17
Shear force in the left abutment and central column in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

	Left Abutment		Central Bent, Central Column	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	786.0	-850.5	633.4	-608.9
1	14144.6	-18441.4	957.2	-817.1
3	9367.5	-11934.0	1031.0	-768.6
5	3259.5	-3807.9	1838.4	-1589.7
6	2389.5	-2969.5	1845.9	-1338.0

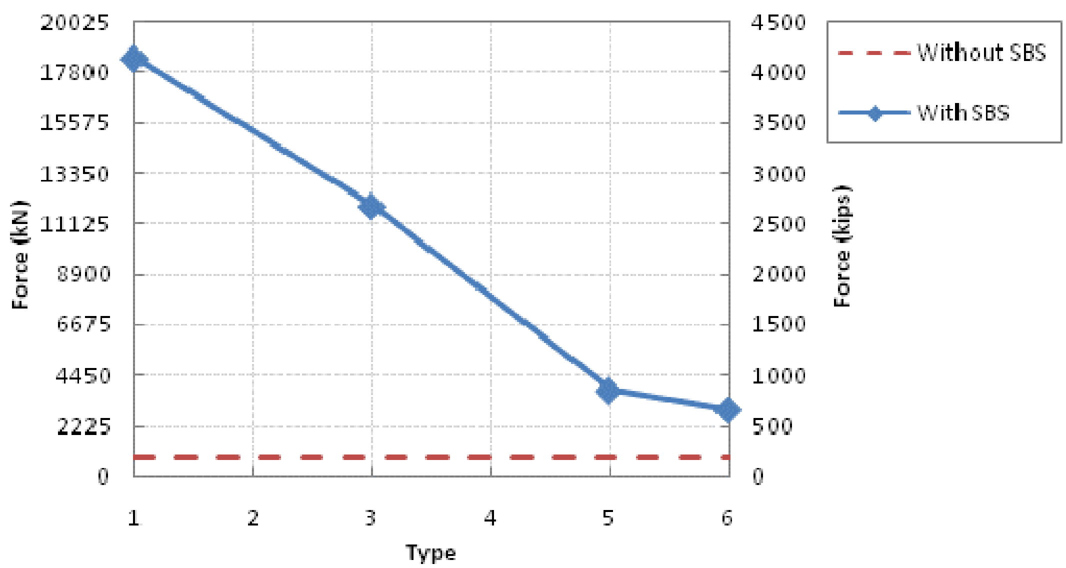


Fig. 94. Maximum shear force in the left abutment in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

For the case under a 0.43g ground motion, Fig. 95 is time history of deck movement for bridge without SBS. Fig. 96 and Fig. 97 are time histories of deck movement for bridges equipped with SBS (Type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively. Fig. 98 is the load-deformation curve of the SBS with 2.54 cm (1 in) gap subjected to the 0.43g ground motion.

Fig. 99 shows time history of shear force in left abutment for bridge without SBS. Fig. 100 and Fig. 101 are time histories of shear force in left abutment for bridges equipped with SBS (Type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively.

Fig. 102 shows time history of shear force in central column of the column bent for bridge without SBS. Fig. 103 and Fig. 104 are time histories of shear force in the same column for bridges equipped with SBS (Type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively.

Maximum values of relative deck displacement and shear forces at selected locations are listed in Table 18, Table 19, and Table 20 Table 21. These values are summarized in Fig. 105, Fig. 106, Fig. 107 and Fig. 108.

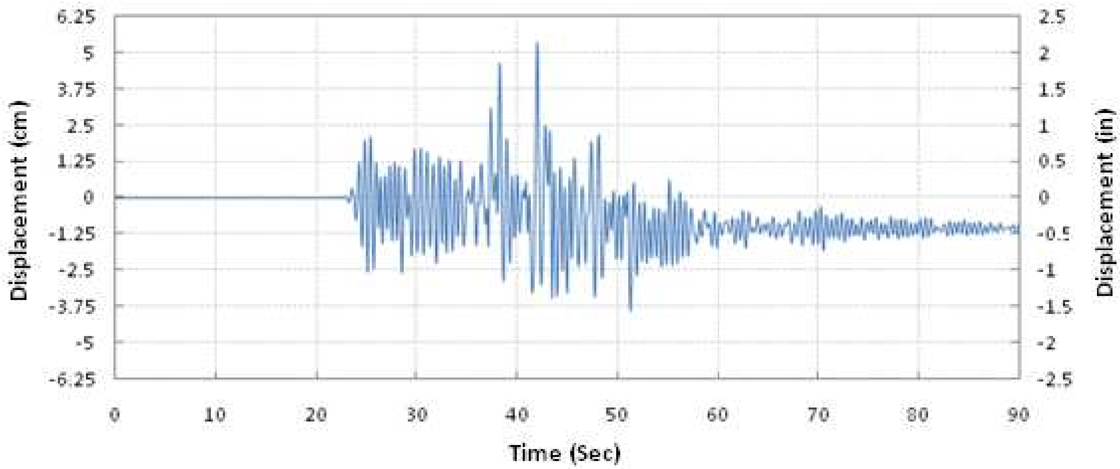


Fig. 95. Displacement of the deck in the bridge without SBS under a 0.43g ground motion.

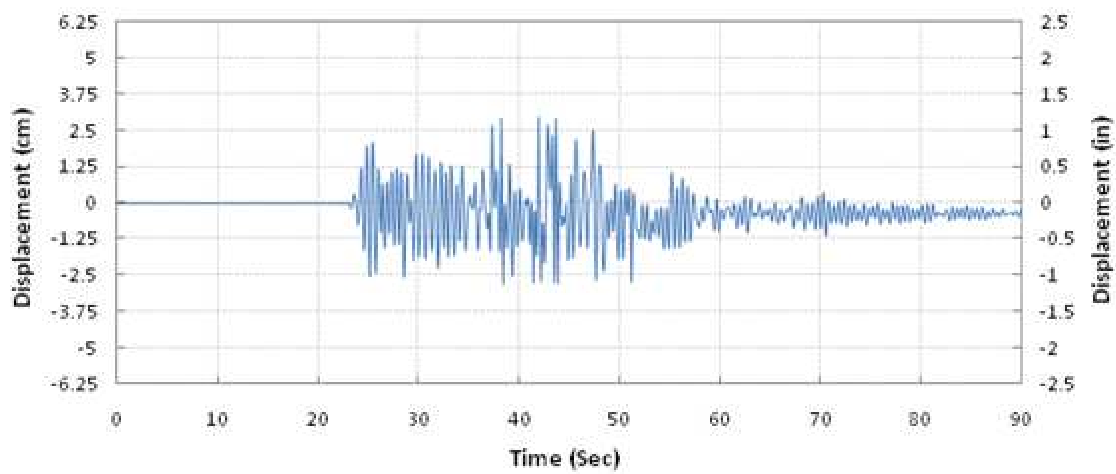


Fig. 96. Displacement of the deck in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

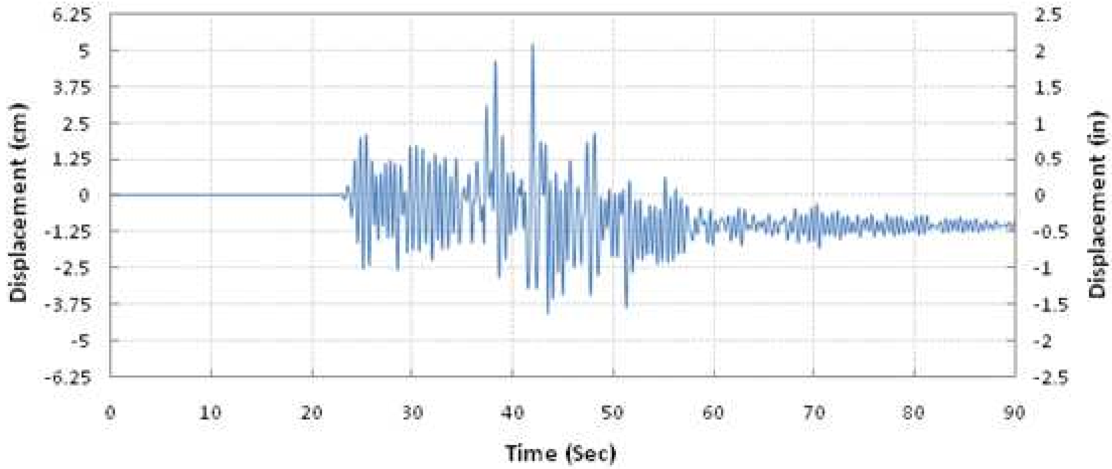
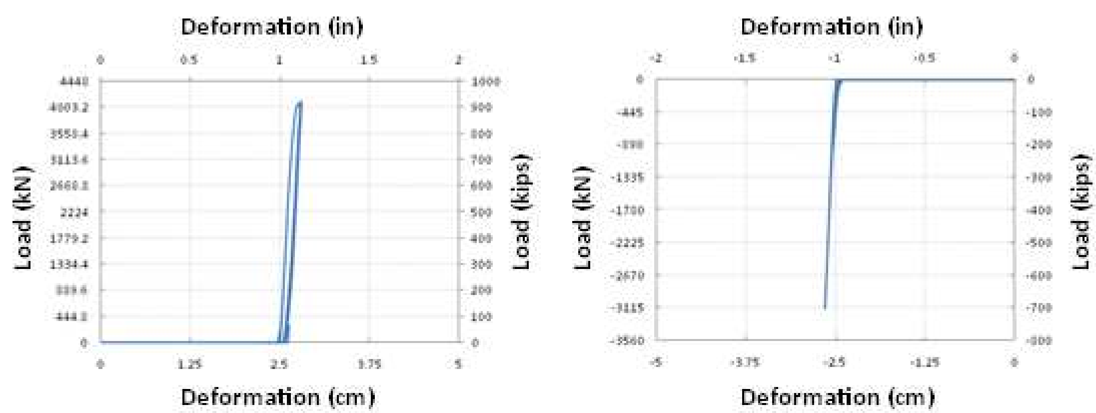


Fig. 97. Displacement of the deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.



(a) (b)

Fig. 98. Load-deformation relationship of the SBS (type1, 2.54 cm (1 in) gap) at the left end of the left deck under a 0.43g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

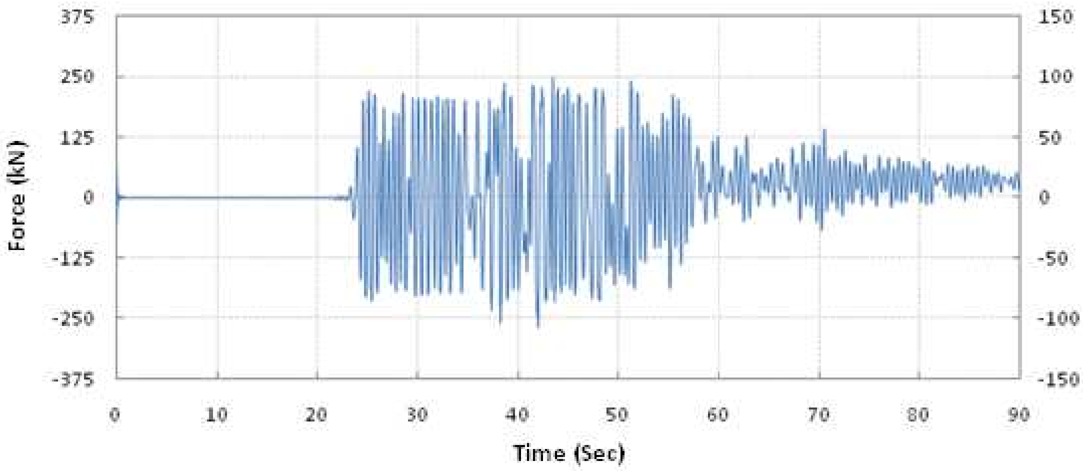


Fig. 99. Shear force in the left abutment in the bridge without SBS under a 0.43g ground motion.

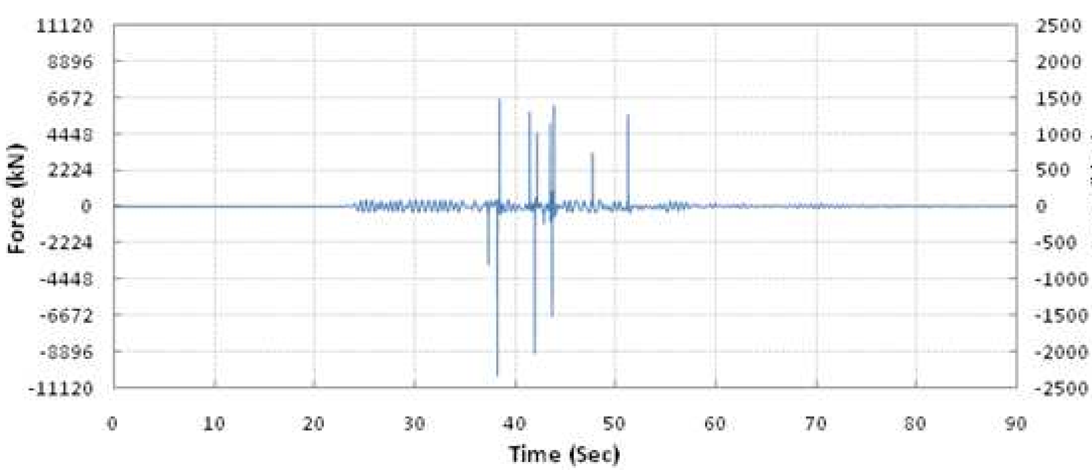


Fig. 100. Shear force in the left abutment in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

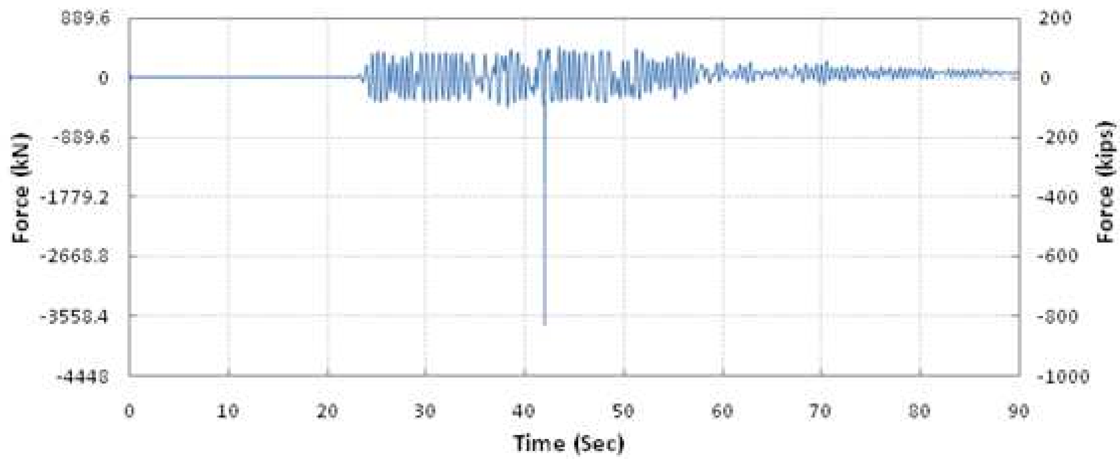


Fig. 101. Shear force in the left abutment in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.

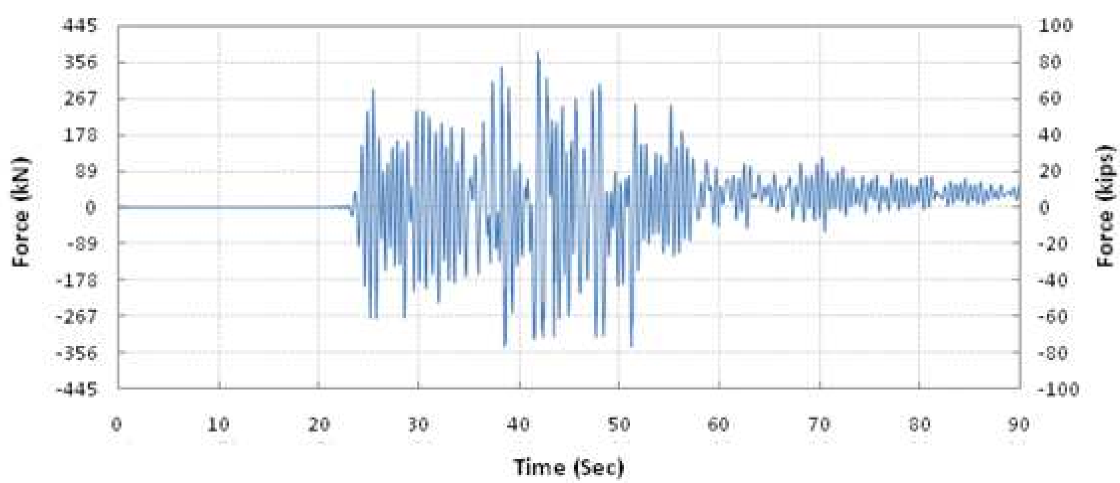


Fig. 102. Shear force in the central column of the bent in the bridge without SBS under a 0.43g ground motion.

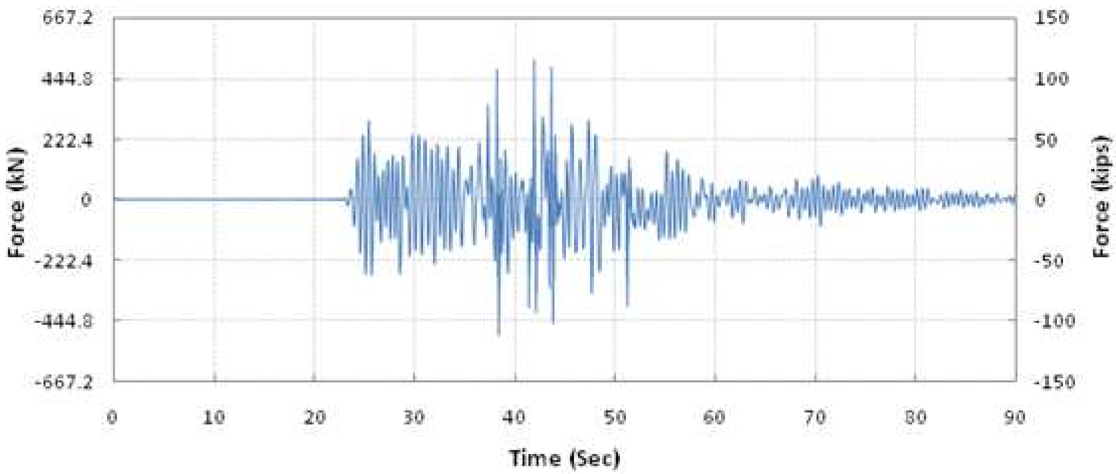


Fig. 103. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

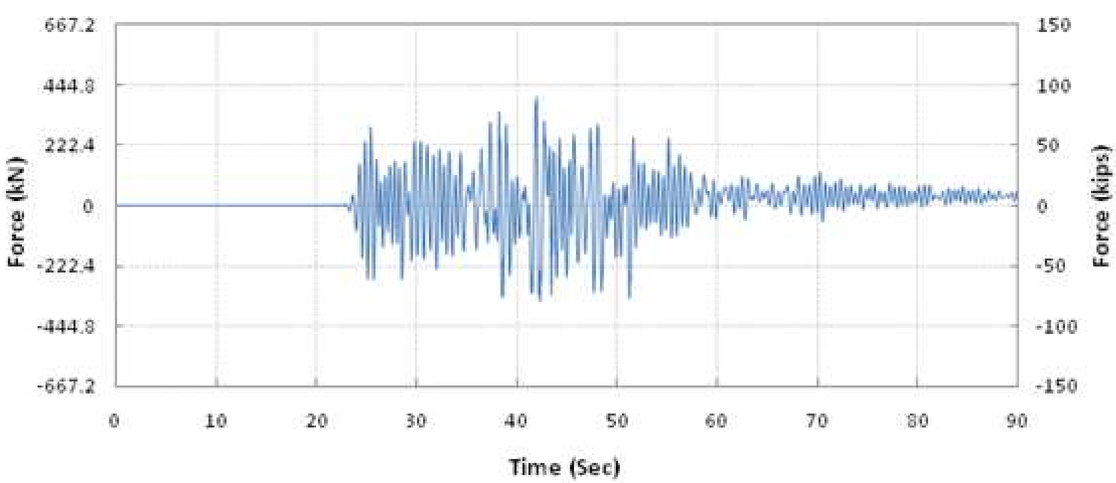


Fig. 104. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.

Table 18
Relative displacement of the deck in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	5.3	3.8	4.5	3.1
1	2.8	2.7	2.0	1.9
3	3.0	2.8	2.1	2.0
5	3.5	3.8	2.8	2.6
6	3.7	4.0	2.8	2.7

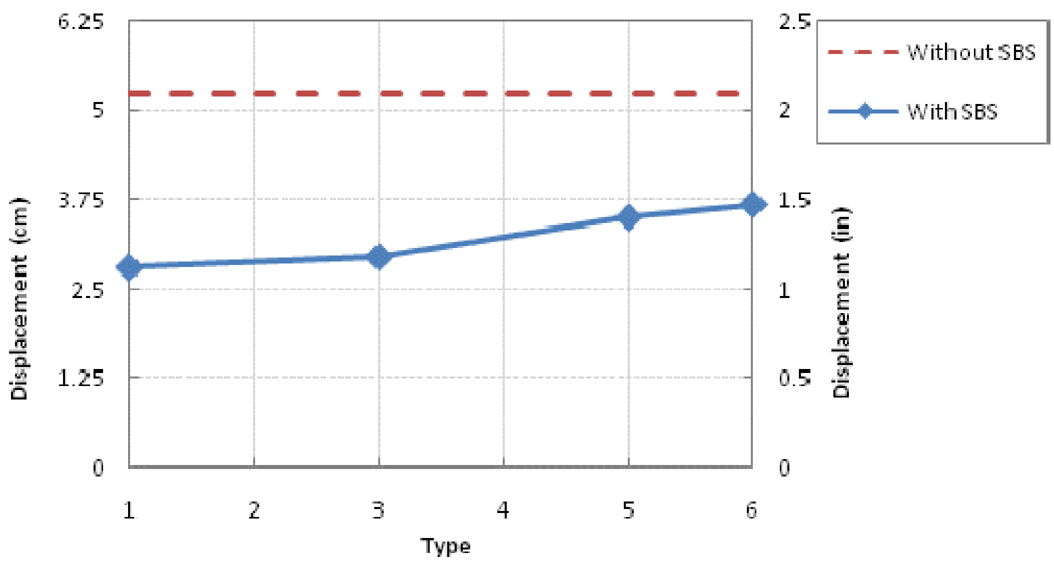


Fig. 105. Relative displacement of the deck in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

Table 19
Shear force in the left abutment and central column in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

SBS	Left Abutment +X direction (kN)	Left Abutment -X direction (kN)	Central Bent, Central Column +X direction (kN)	Central Bent, Central Column -X direction (kN)
w/o SBS	441.4	-473.7	381.6	-342.9
1	6543.0	-10399.4	512.9	-494.2
3	4648.2	-6049.3	432.8	-466.2
5	2496.2	-2119.9	455.5	-427.9
6	1820.1	-1680.0	370.5	-459.0

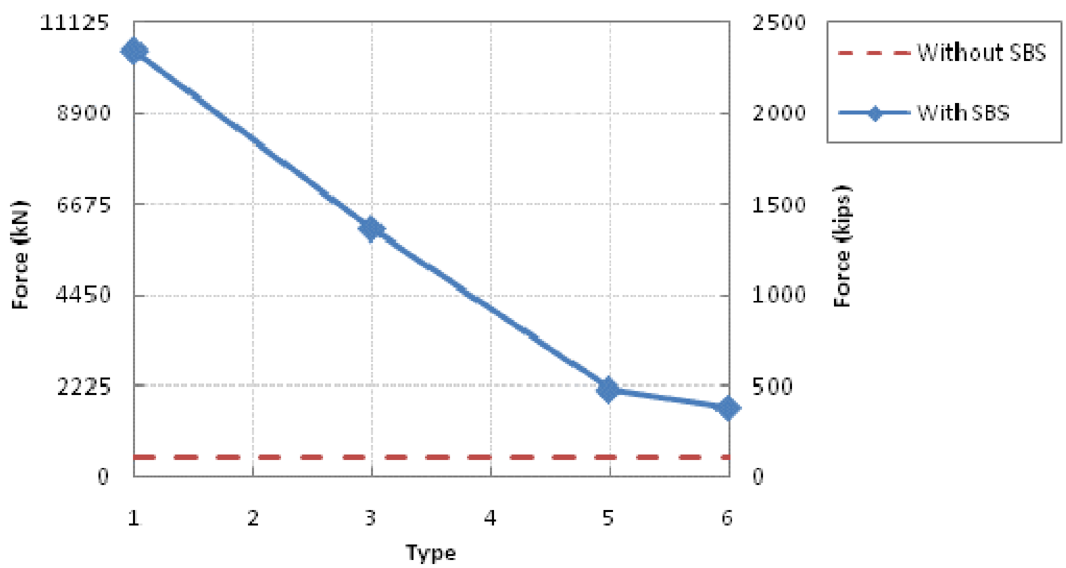


Fig. 106. Maximum shear force in the left abutment in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

Table 20
Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

SBS	Left end of deck Inward (cm)	Left end of deck Outward (cm)	Right end of deck Inward (cm)	Right end of deck Outward (cm)
w/o SBS	5.3	3.8	4.5	3.1
1	5.2	4.1	4.2	3.6
3	5.2	4.0	4.2	3.5
5	5.3	3.9	4.4	3.3
6	5.3	3.9	4.4	3.2

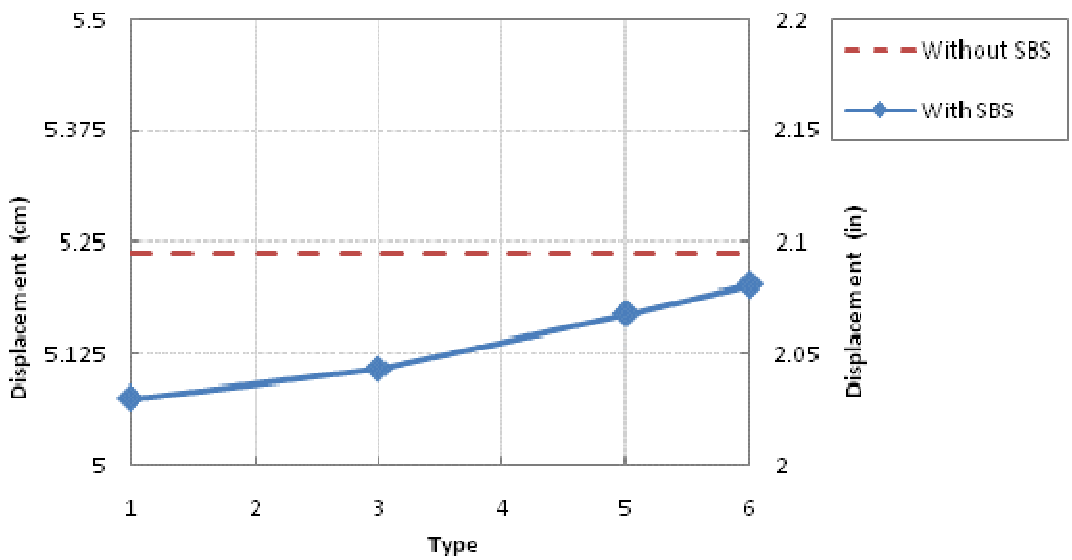


Fig. 107. Relative displacement of the deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

Table 21
Shear force in the left abutment and central column in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

	Left Abutment		Central Bent, Central Column	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	441.4	-473.7	381.6	-342.9
1	460.8	-3696.3	400.3	-353.6
3	458.1	-2590.1	383.9	-342.9
5	450.1	-1208.1	383.9	-342.9
6	447.0	-838.0	383.9	-342.9

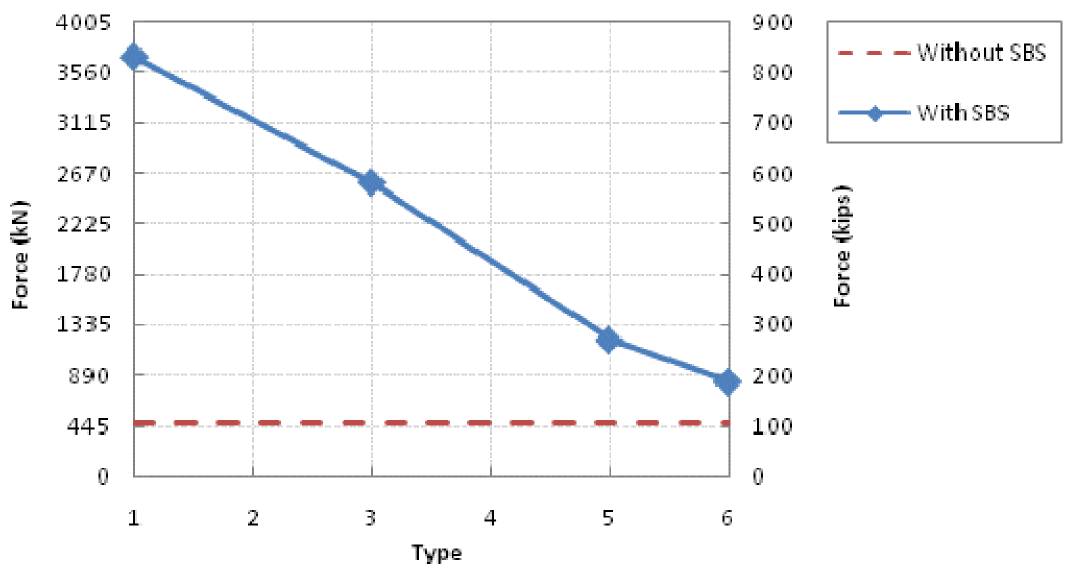


Fig. 108. Maximum shear force in the left abutment in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

4.2.2.3 Three-span simply-supported bridge

In this analysis, a three span bridge model is tested under two sets of ground motions (1.01g and 0.43g). Time history data of deck movement of the left deck and shear force in the left abutment are presented as examples.

For the case under a 1.01g ground motion, Fig. 109 is time history of movement of the left deck for bridge without SBS. Fig. 110 and Fig. 111 are time histories of movement of the left deck for bridges equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively. Fig. 112 is time history of movement of the central deck for bridge without SBS. Fig. 113 and Fig. 114 are time histories of movement of the central deck for bridges equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively. Fig. 115, Fig. 116 and Fig. 117 are the load-deformation curves of the SBS at various locations with 5.08 cm (2 in) gap subjected to the 1.01g ground motion.

Fig. 118 shows a time history of shear force in left abutment for bridge without SBS. Fig. 119 and Fig. 120 are time histories of shear force in left abutment for bridges equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively.

Fig. 121 shows a time history of shear force in central column of the left column bent for bridge without SBS. Fig. 122 and Fig. 123 are time histories of shear force in the same column for bridges equipped with SBS (Type1) and have 5.08 cm (2 in) and 10.16 cm (4 in) gap, respectively.

Maximum values of relative deck displacement and shear forces at selected locations are listed in Table 22, Table 23, Table 24 and Table 25. These values are summarized in Fig. 124, Fig. 125, Fig. 126 and Fig. 127.

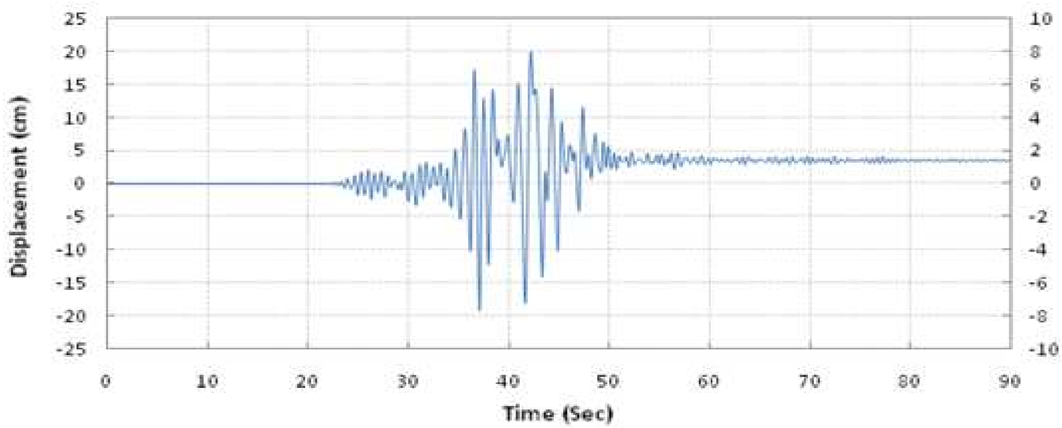


Fig. 109. Displacement of the left deck in the bridge without SBS under a 1.01g ground motion.

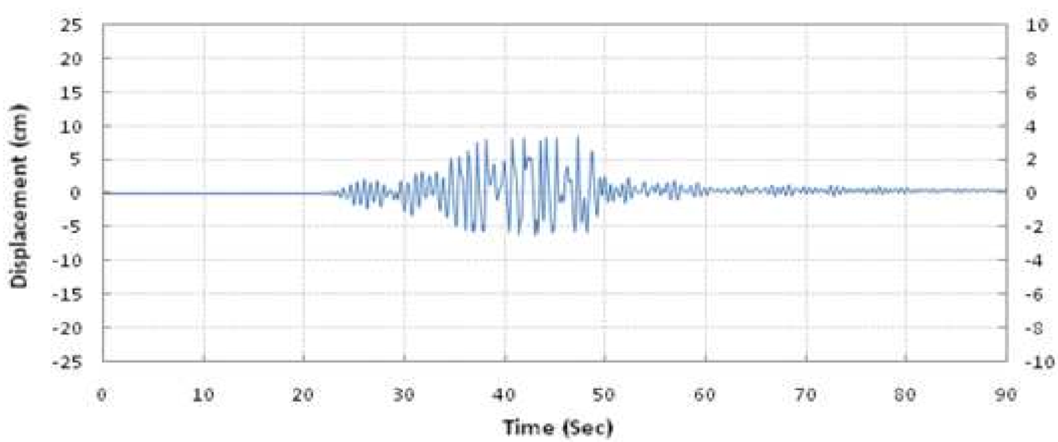


Fig. 110. Displacement of the left deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

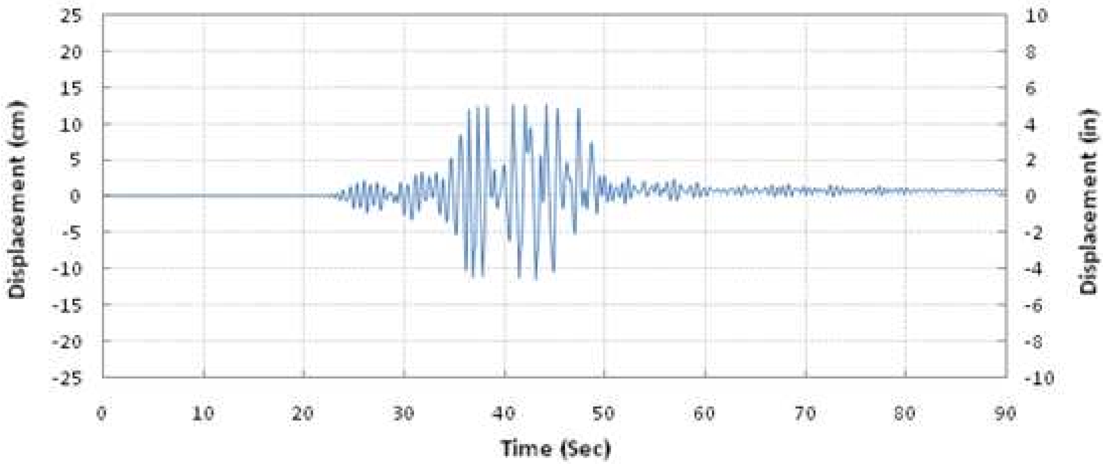


Fig. 111. Displacement of the left deck in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.

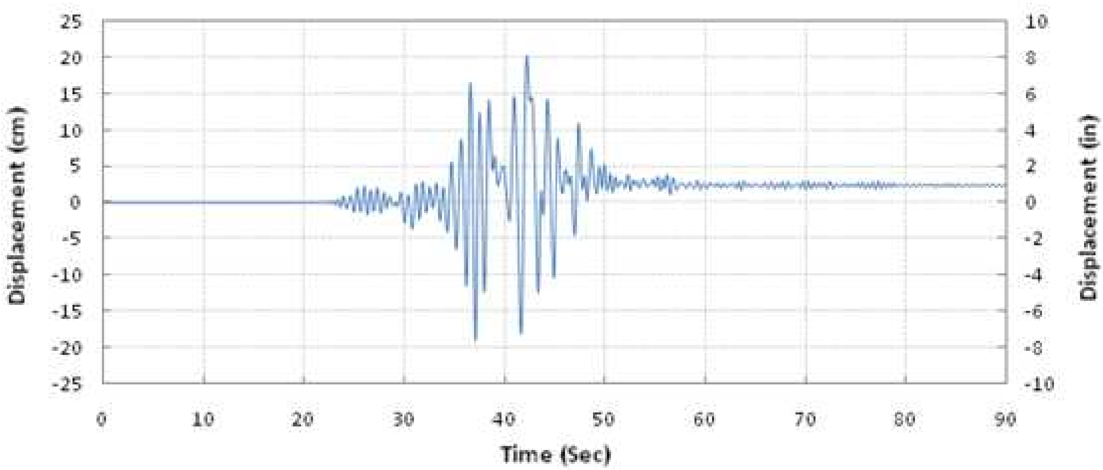


Fig. 112. Displacement of the central deck in the bridge without SBS under a 1.01g ground motion.

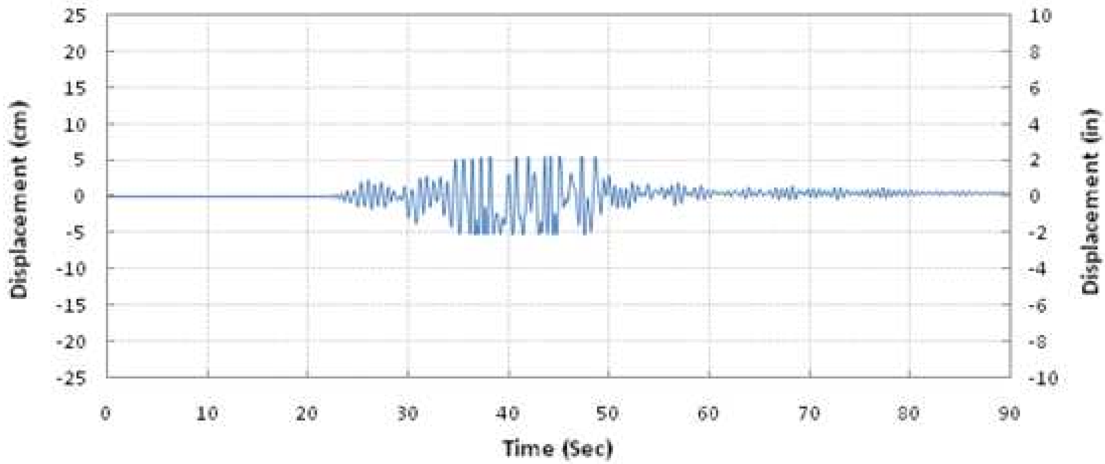


Fig. 113. Displacement of the central deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

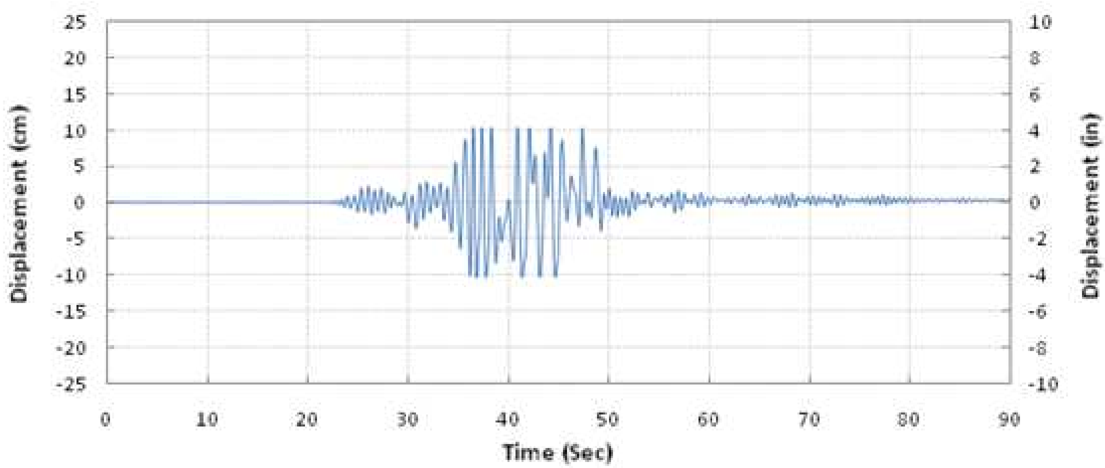
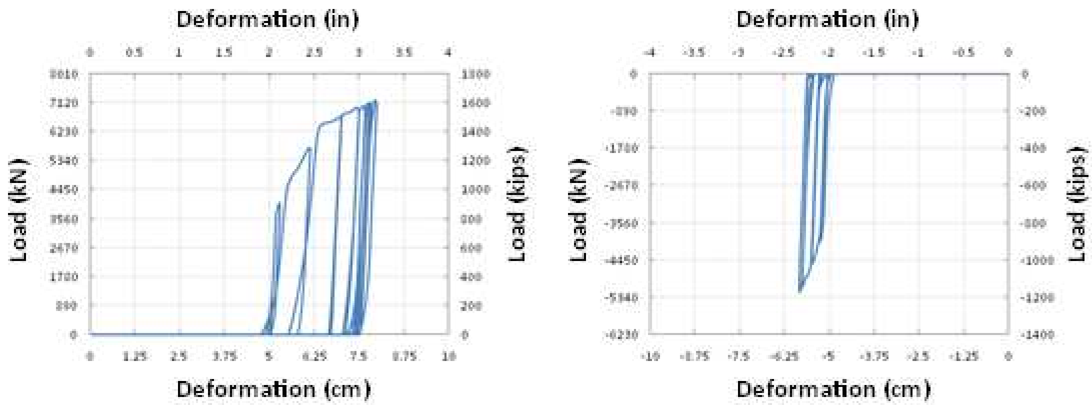


Fig. 114. Displacement of the central deck in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.



(a) (b)

Fig. 115. Load-deformation relationship of the SBS (type1, 5.08 cm (2 in) gap) at the left end of the left deck under a 1.01g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

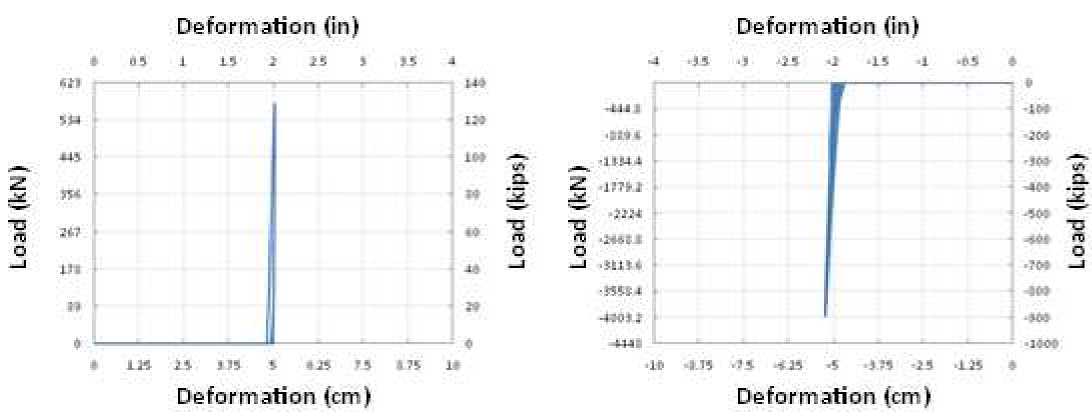


Fig. 116. Load-deformation relationship of the SBS (type1, 5.08 cm (2 in) gap) at the right end of the left deck under a 1.01g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

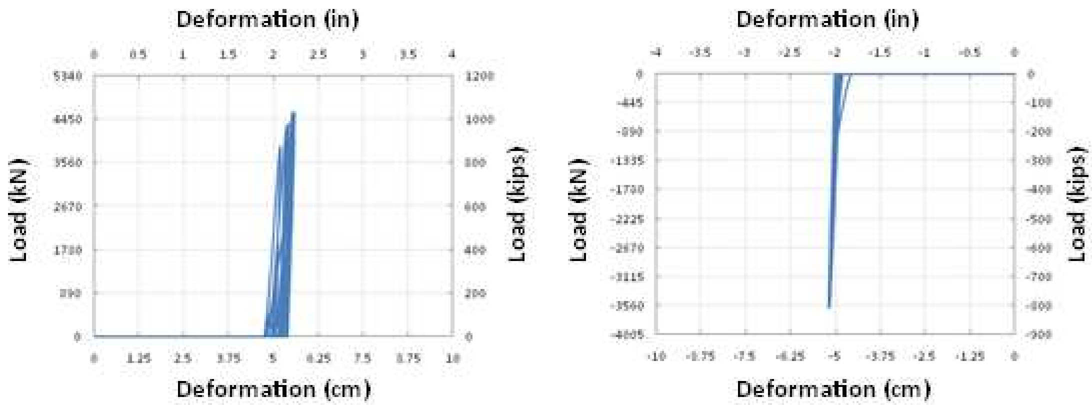


Fig. 117. Load-deformation relationship of the SBS (type1, 5.08 cm (2 in) gap) at the left end of the central deck under a 1.01g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

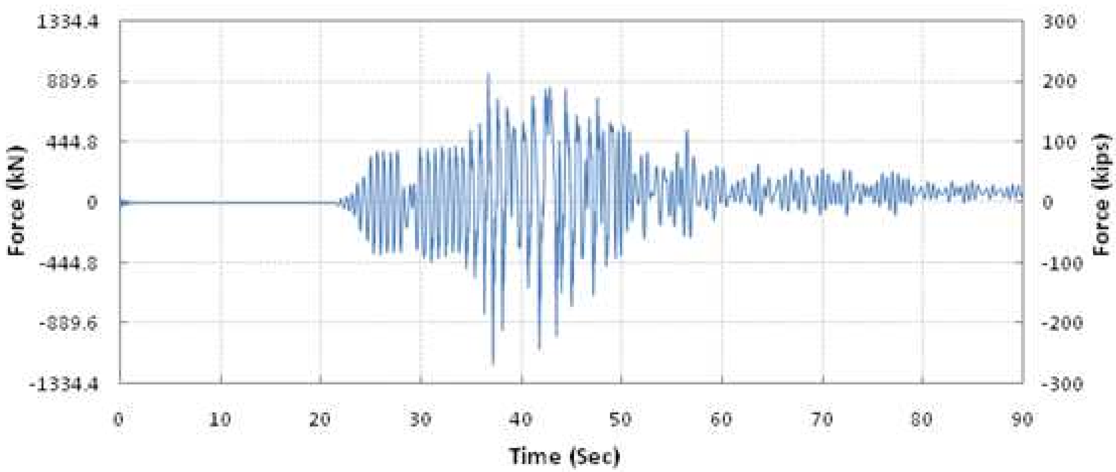


Fig. 118. Shear force in the left abutment in the bridge without SBS under a 1.01g ground motion.

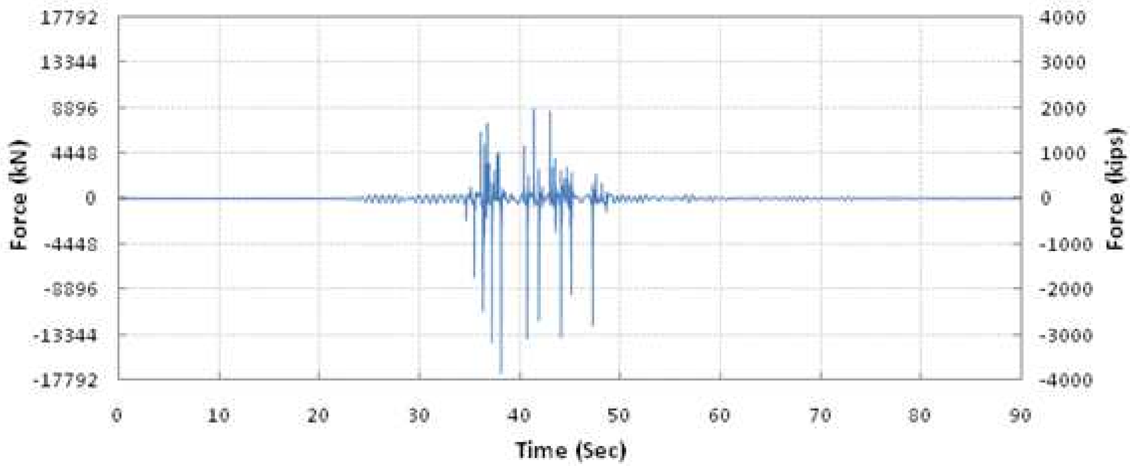


Fig. 119. Shear force in the left abutment in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

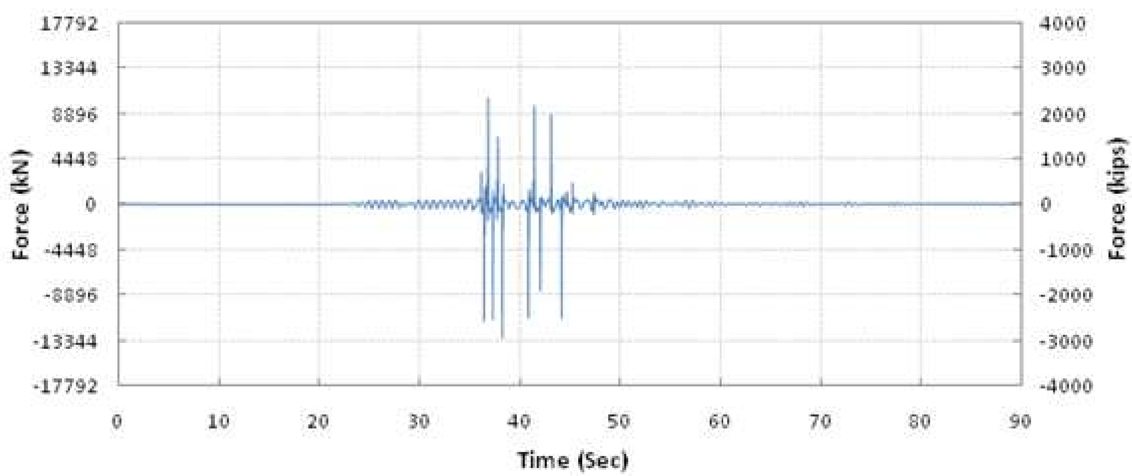


Fig. 120. Shear force in the left abutment in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.

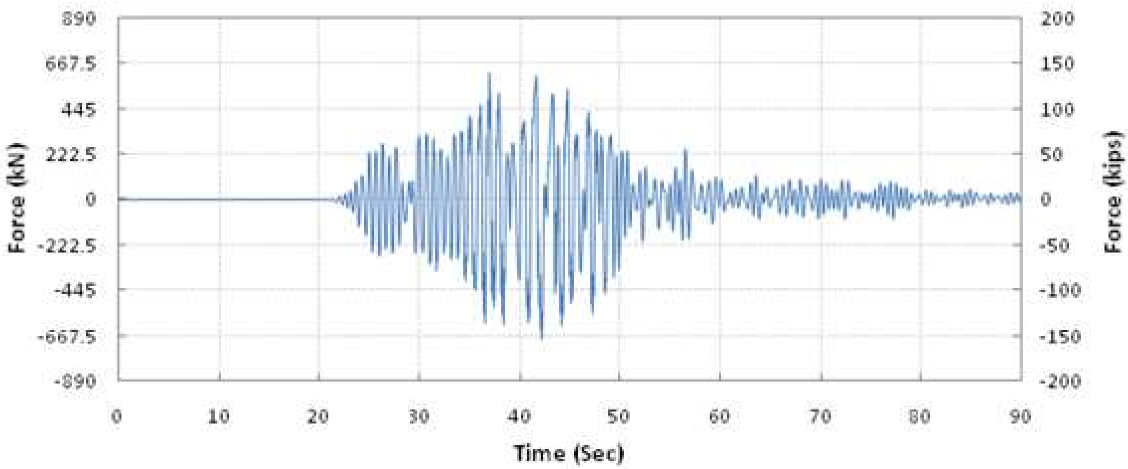


Fig. 121. Shear force in the central column of the bent in the bridge without SBS under a 1.01g ground motion.

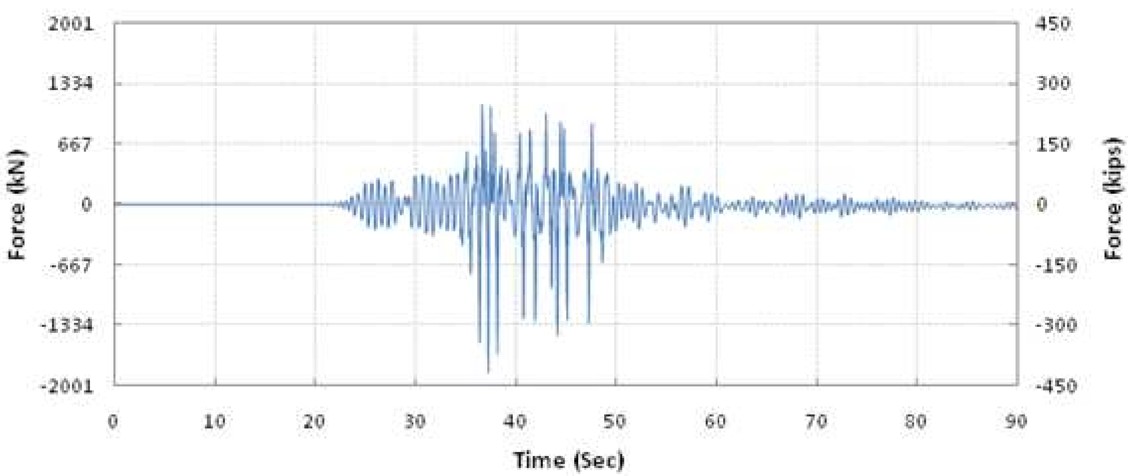


Fig. 122. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 1.01g ground motion.

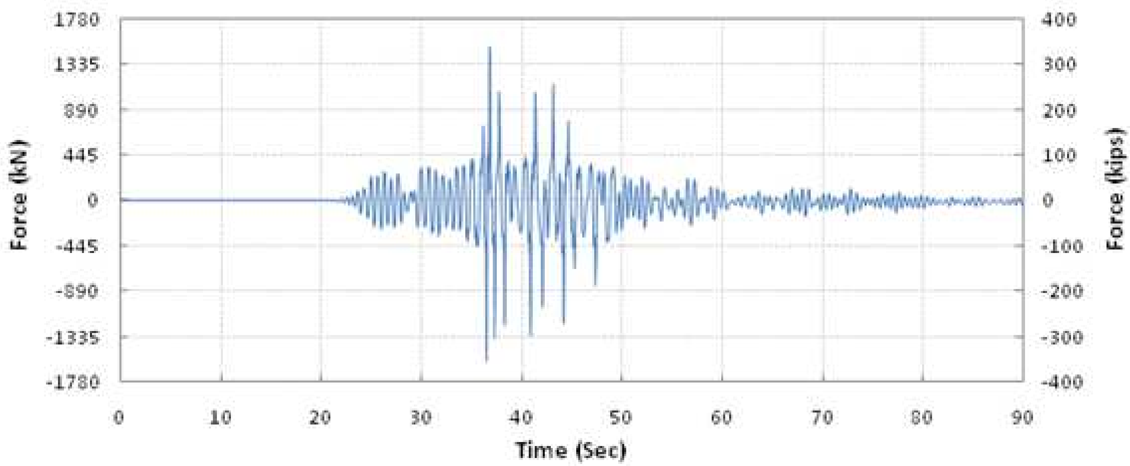


Fig. 123. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 10.16 cm (4 in) gap) under a 1.01g ground motion.

Table 22
Relative displacement of the left deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	20.1	19.3	18.2	17.8
1	8.1	5.9	5.5	5.1
3	9.5	6.1	5.7	5.3
5	13.8	11.4	9.9	8.5
6	17.1	15.2	13.3	12.6

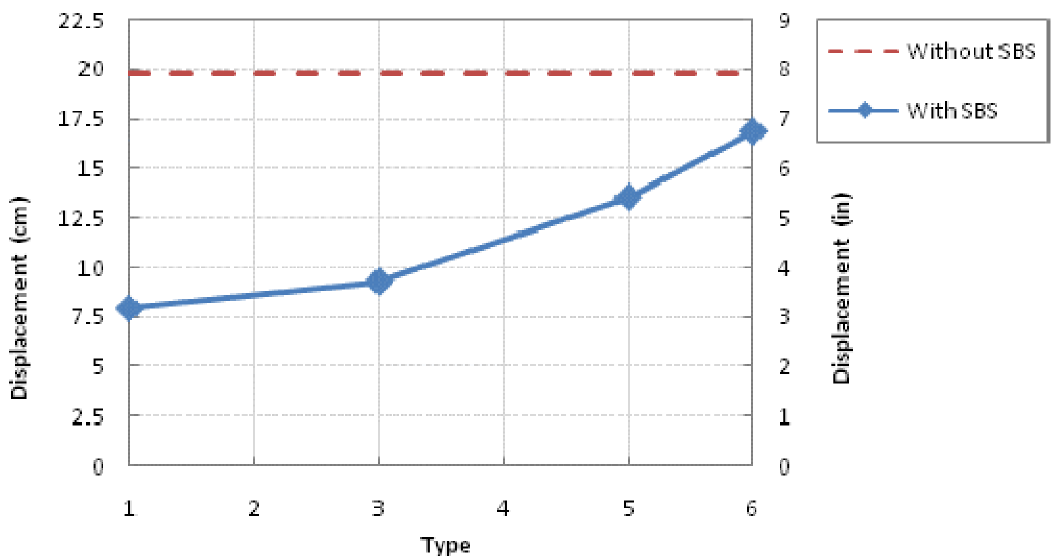


Fig. 124. Relative displacement of the left deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

Table 23
Shear force in the left abutment and central column in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

	Left Abutment		Central Bent, Central Column	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	951.4	-1197.4	624.9	-682.8
1	8913.8	-17191.5	1096.4	-1847.7
3	6062.6	-11209.0	1238.8	-2013.6
5	2998.0	-3199.4	1449.2	-1806.3
6	2567.4	-2602.5	1471.0	-1619.1

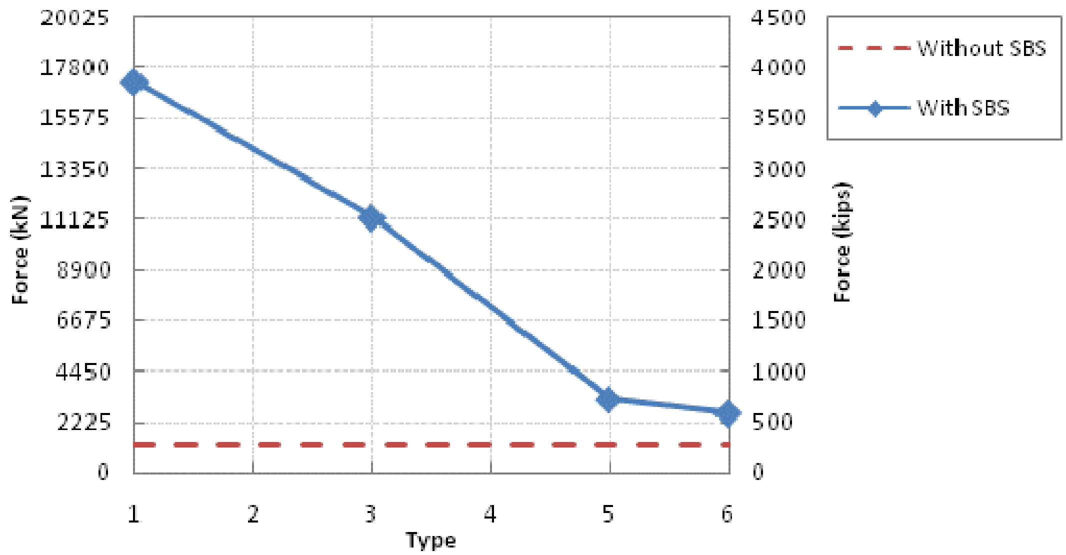


Fig. 125. Maximum shear force in the left abutment in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 1.01g ground motion.

Table 24
Relative displacement of the left deck in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	20.1	19.3	18.2	17.8
1	12.4	11.4	10.4	10.2
3	13.3	12.2	10.4	10.4
5	19.6	17.6	16.2	14.0
6	20.4	17.3	17.0	14.0

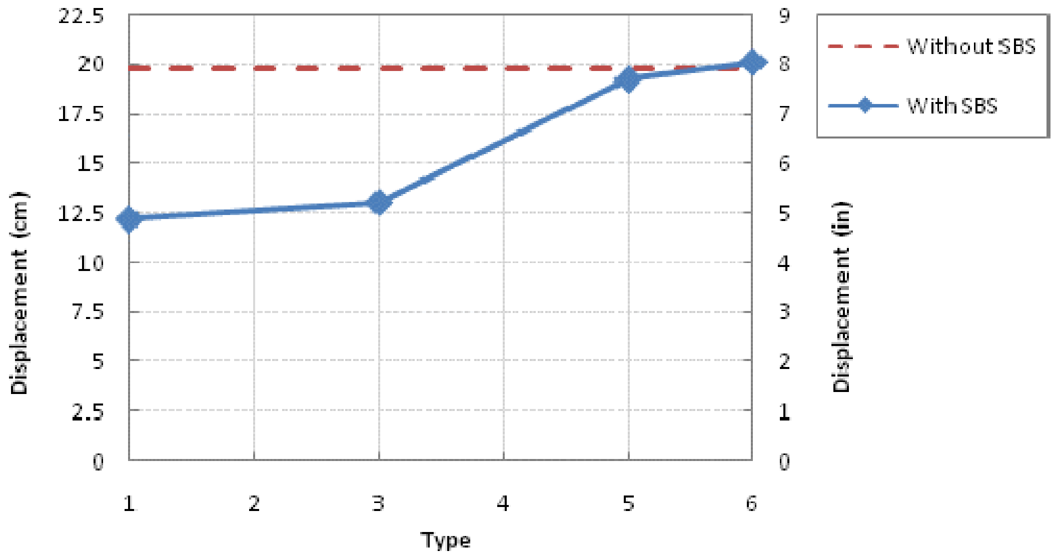


Fig. 126. Relative displacement of the deck in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

Table 25
Shear force in the left abutment and central column in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

	Left Abutment		Central Bent, Central Column	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	951.4	-1197.4	624.9	-682.8
1	10257.1	-13077.1	1518.1	-1581.9
3	7717.3	-9300.8	1534.6	-1570.6
5	2774.2	-3300.0	1589.7	-2077.2
6	2057.6	-2606.5	1563.0	-1948.7

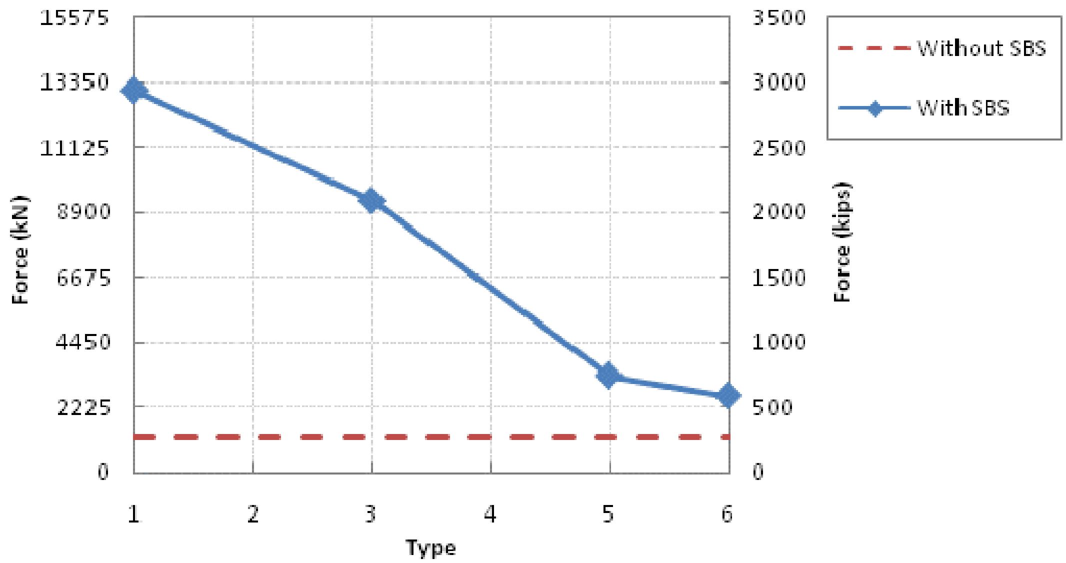


Fig. 127. Maximum shear force in the left abutment in the bridge equipped with various SBS with 10.16 cm (4 in) gap under a 1.01g ground motion.

For the case under a 0.43g ground motion, Fig. 128 is time history of movement of the left deck for bridge without SBS. Fig. 129 and Fig. 130 are time history of movement of the left deck for bridges equipped with SBS (Type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively. Fig. 131 is time history of movement of the central deck for bridge without SBS. Fig. 132 and Fig. 133 are time histories of movement of the central deck for bridges equipped with SBS (Type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively. Fig. 134 and Fig. 135 are the load-deformation curves of the SBS at various locations with 2.54 cm (1 in) gap subjected to the 0.43g ground motion.

Fig. 136 shows time history of shear force in left abutment for bridge without SBS. Fig. 137 and Fig. 138 are time histories of shear force in left abutment for bridges equipped with SBS (Type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively.

Fig. 139 shows time history of shear force in central column of the left column bent for bridge without SBS. Fig. 140 and Fig. 141 are time histories of shear force in the same column for bridges equipped with SBS (Type1) and have 2.54 cm (1 in) and 5.08 cm (2 in) gap, respectively.

Maximum values of relative deck displacement and shear forces at selected locations are listed in Table 26, Table 27, Table 28 and Table 29. These values are summarized in Fig. 142, Fig. 143, Fig. 144 and Fig. 145.

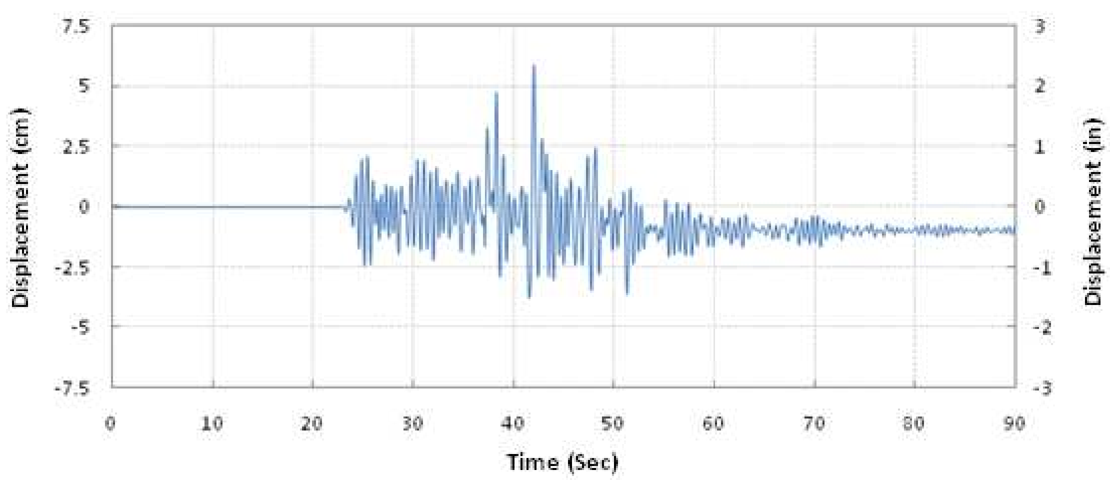


Fig. 128. Displacement of the left deck in the bridge without SBS under a 0.43g ground motion.

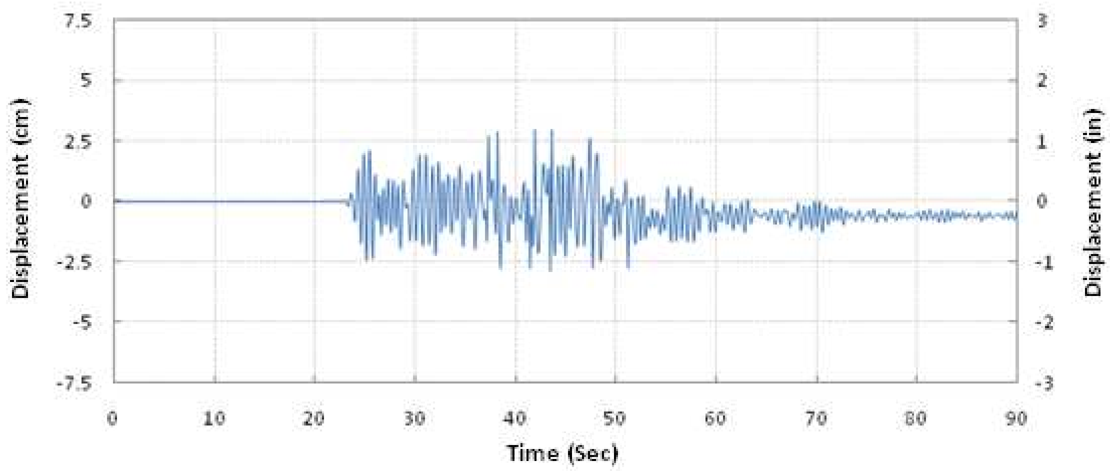


Fig. 129. Displacement of the left deck in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

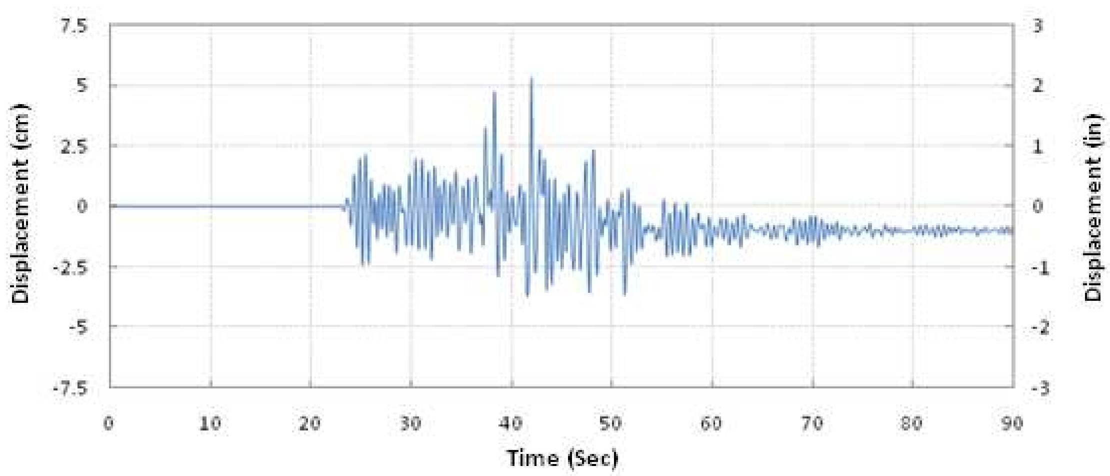


Fig. 130. Displacement of the left deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.

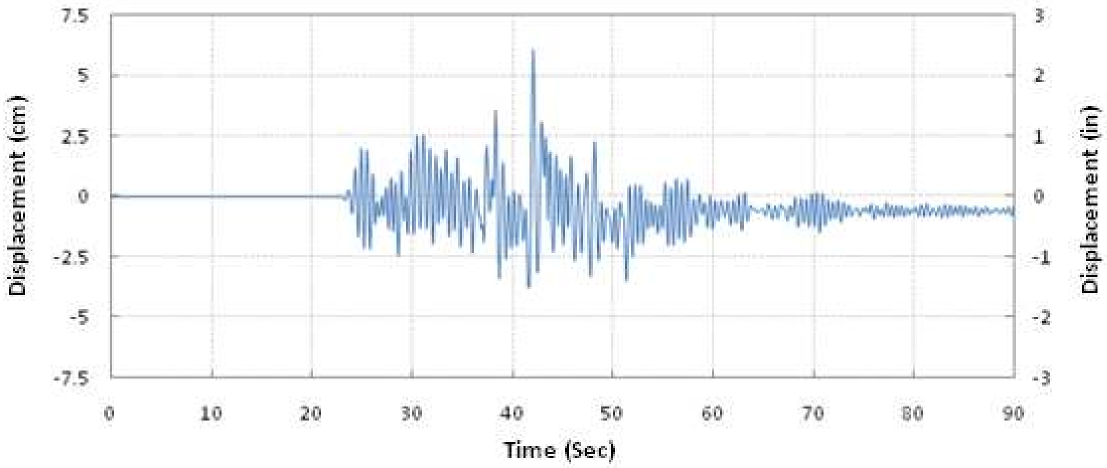


Fig. 131. Displacement of the central deck in the bridge without SBS under a 0.43g ground motion.

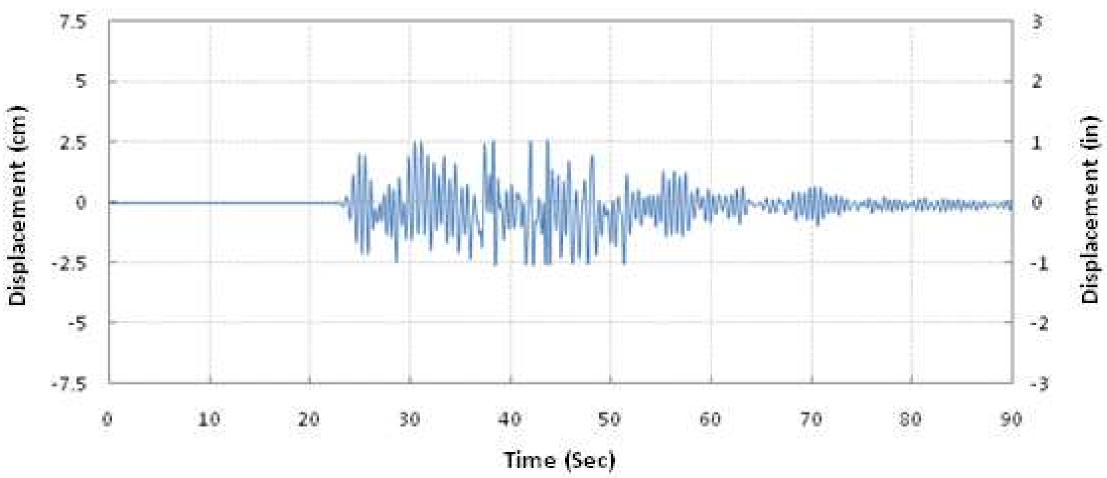


Fig. 132. Displacement of the central deck in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

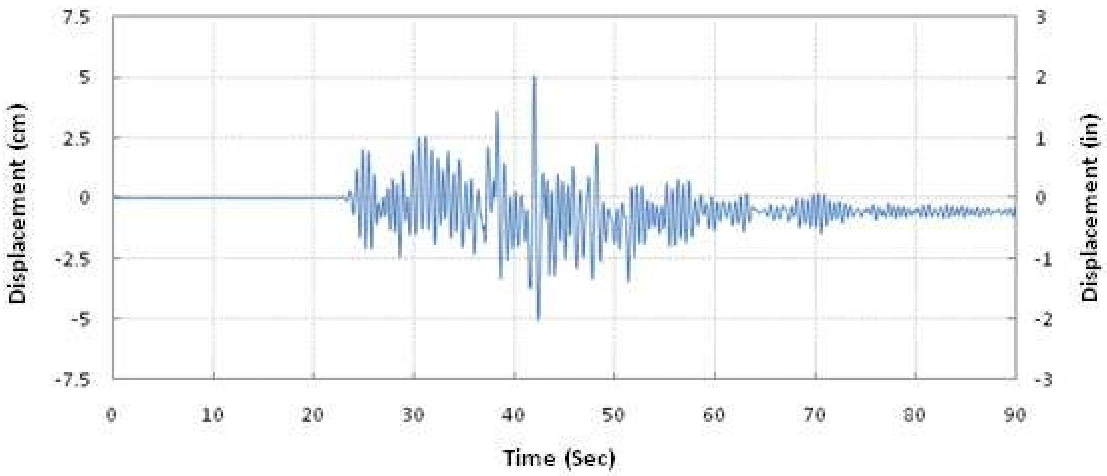
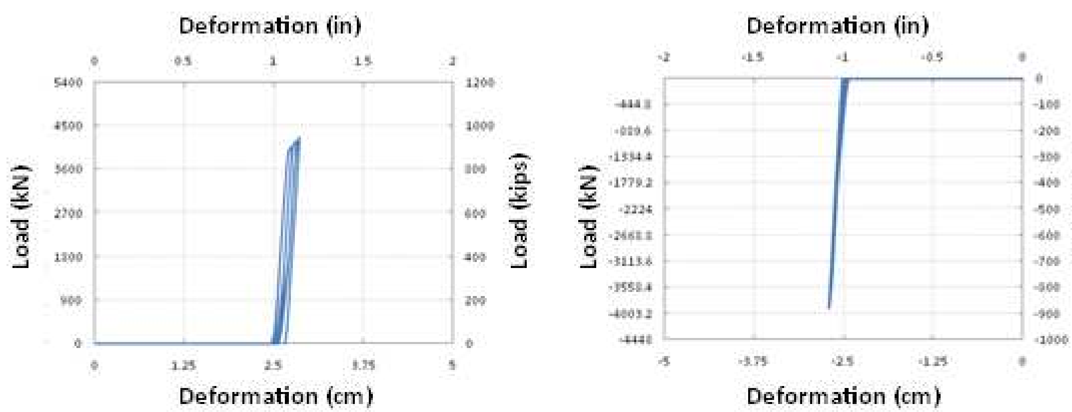
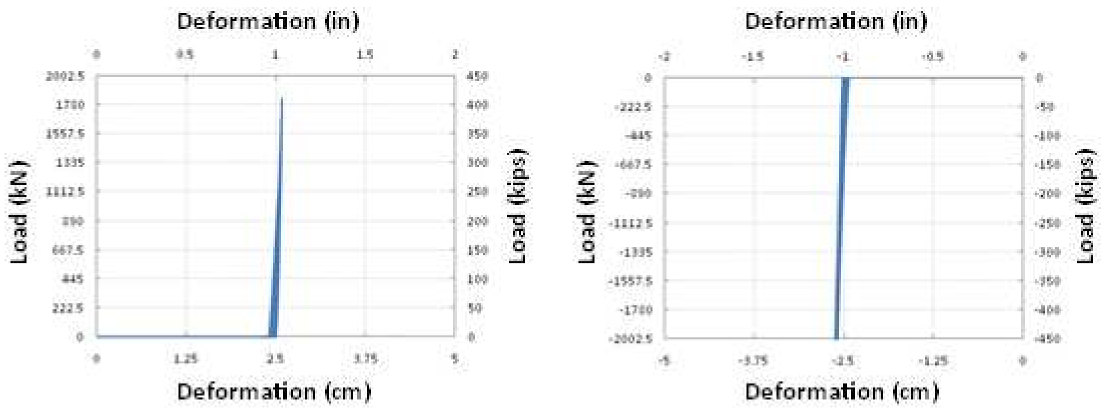


Fig. 133. Displacement of the central deck in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.



(a) (b)

Fig. 134. Load-deformation relationship of the SBS (type1, 2.54 cm (1 in) gap) at the left end of the left deck under a 0.43g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.



(a) (b)

Fig. 135. Load-deformation relationship of the SBS (type1, 2.54 cm (1 in) gap) at the left end of the central deck under a 0.43g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

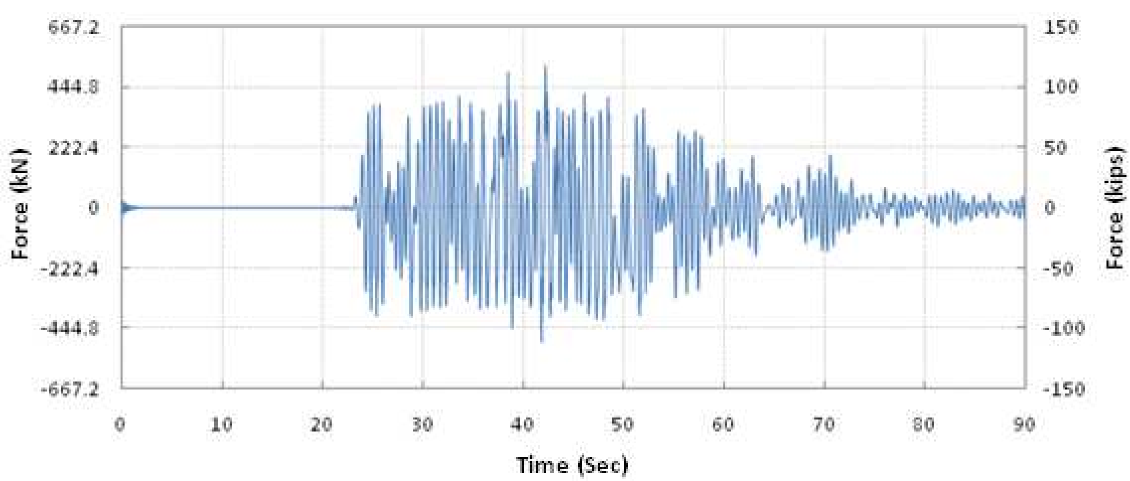


Fig. 136. Shear force in the left abutment in the bridge without SBS under a 0.43g ground motion.

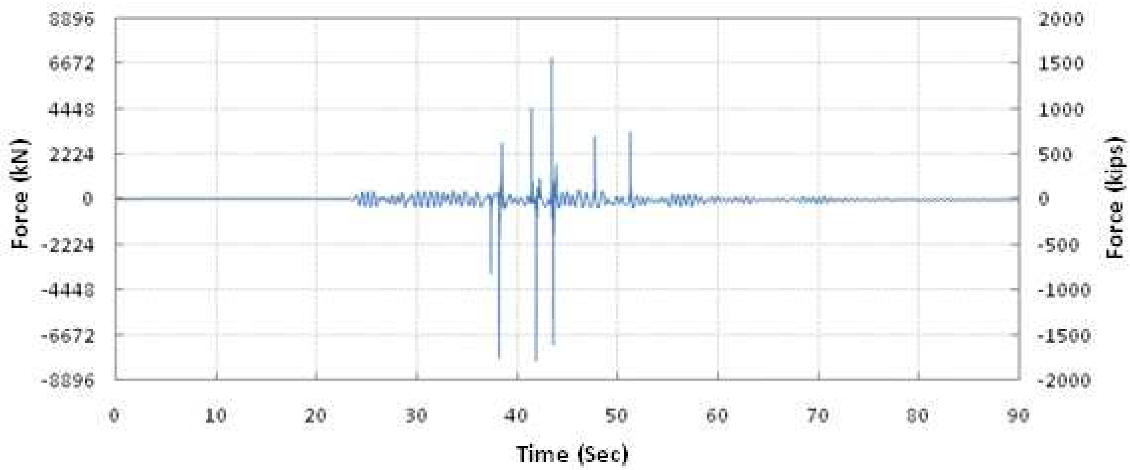


Fig. 137. Shear force in the left abutment in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

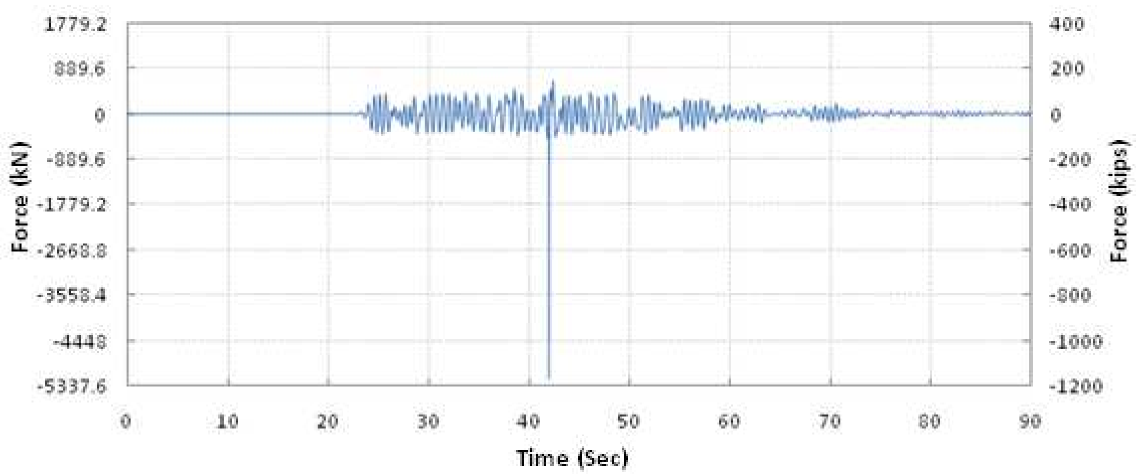


Fig. 138. Shear force in the left abutment in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.

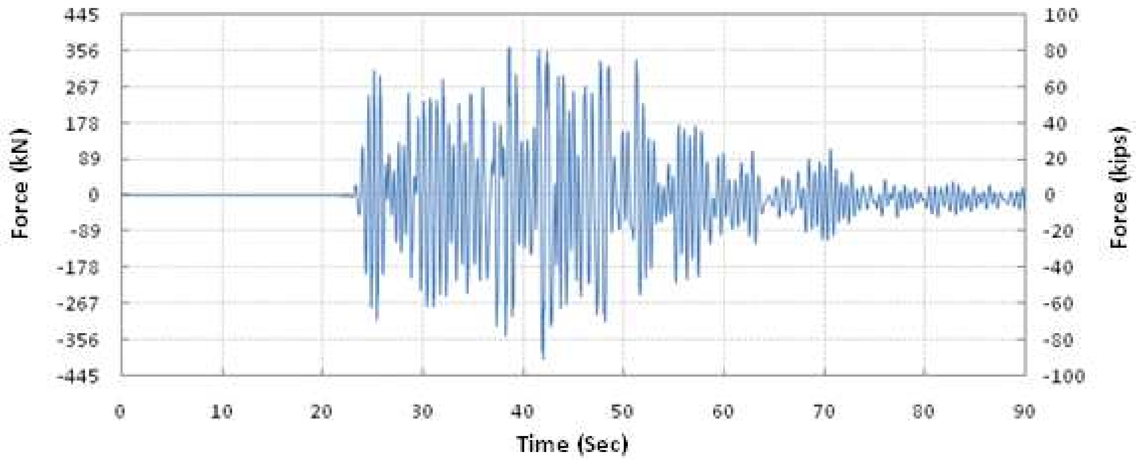


Fig. 139. Shear force in the central column of the bent in the bridge without SBS under a 0.43g ground motion.

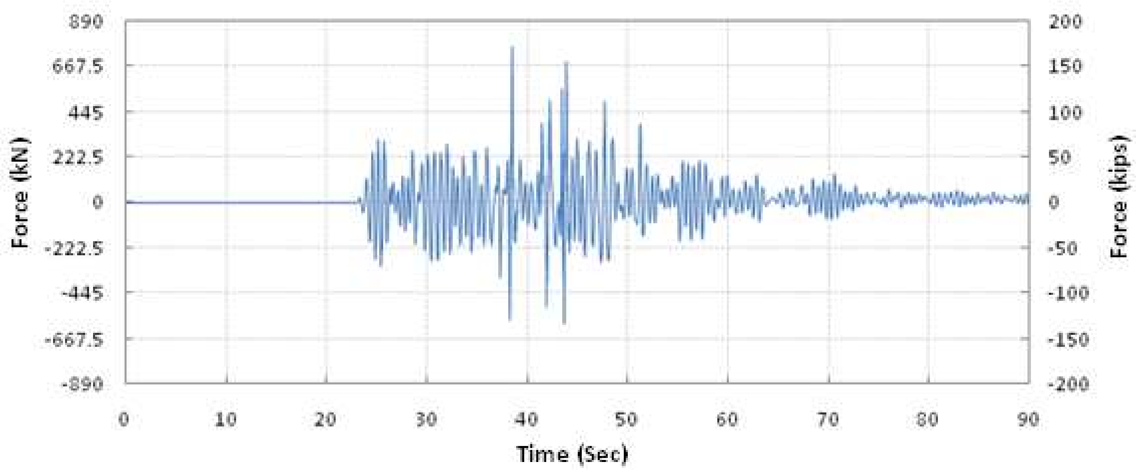


Fig. 140. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

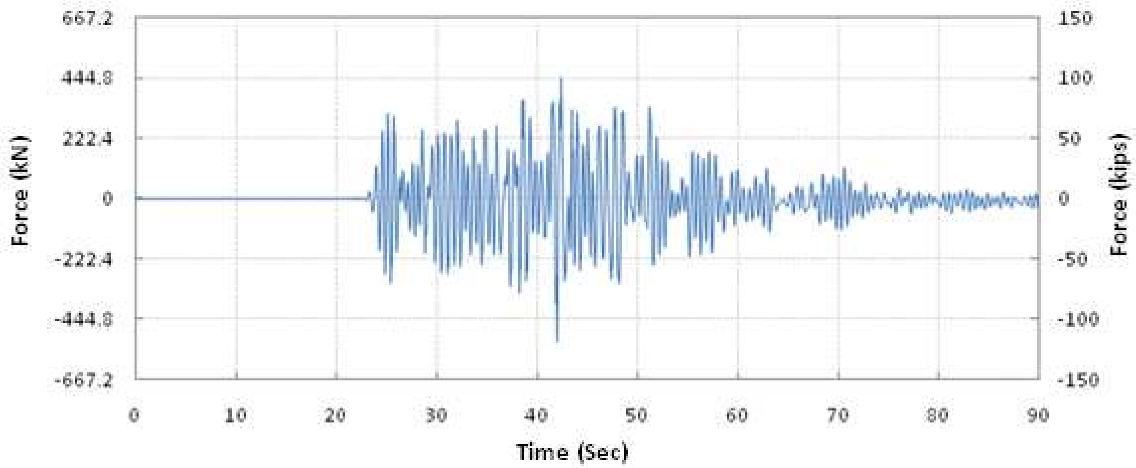


Fig. 141. Shear force in the central column of the bent in the bridge equipped with SBS (type1, 5.08 cm (2 in) gap) under a 0.43g ground motion.

Table 26
Relative displacement of the left deck in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	5.9	3.7	5.0	2.7
1	2.9	2.7	2.3	1.8
3	3.1	2.9	2.6	2.0
5	3.7	3.7	2.6	2.3
6	3.9	4.1	2.6	2.6

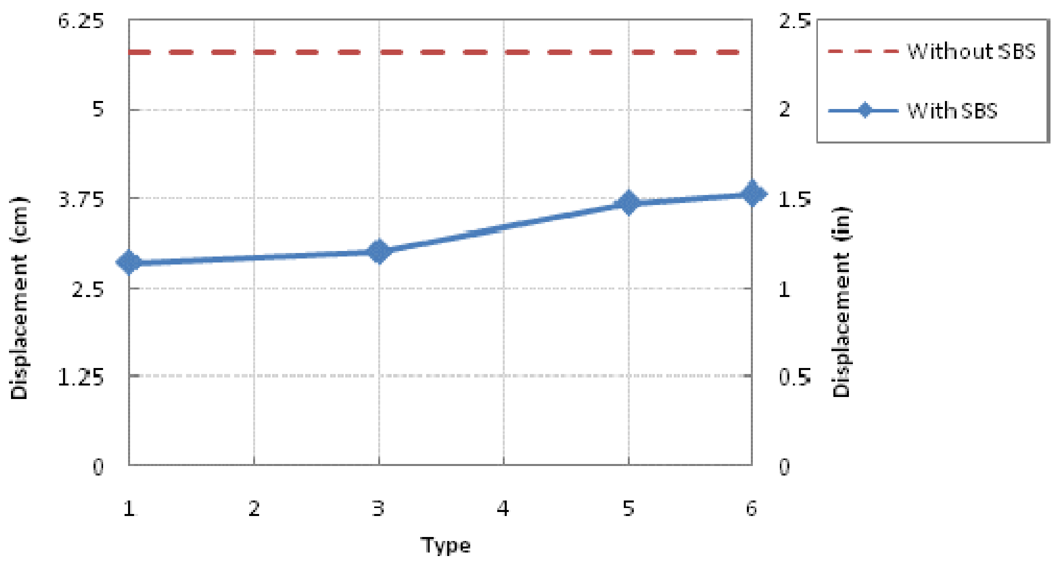


Fig. 142. Relative displacement of the left deck in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

Table 27
Shear force in the left abutment and central column in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

	Left Abutment		Central Bent, Central Column	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	521.3	-494.6	365.6	-403.9
1	6836.6	-7895.2	765.9	-593.8
3	4013.9	-4390.2	794.4	-588.9
5	1946.0	-1914.9	582.7	-551.6
6	1567.5	-1386.4	596.9	-559.1

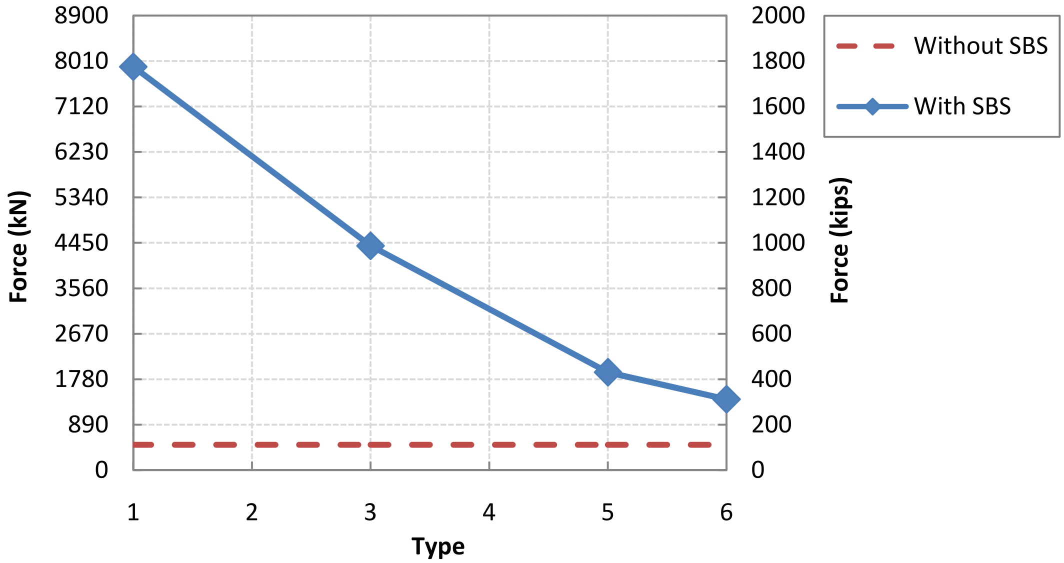


Fig. 143. Maximum shear force in the left abutment in the bridge equipped with various SBS with 2.54 cm (1 in) gap under a 0.43g ground motion.

Table 28
Relative displacement of the left deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

	Left end of deck		Right end of deck	
SBS	Inward (cm)	Outward (cm)	Inward (cm)	Outward (cm)
w/o SBS	5.9	3.7	5.0	2.7
1	5.2	3.7	4.1	2.8
3	5.3	3.7	4.1	3.0
5	5.6	3.7	4.3	2.7
6	5.7	3.7	4.4	2.7

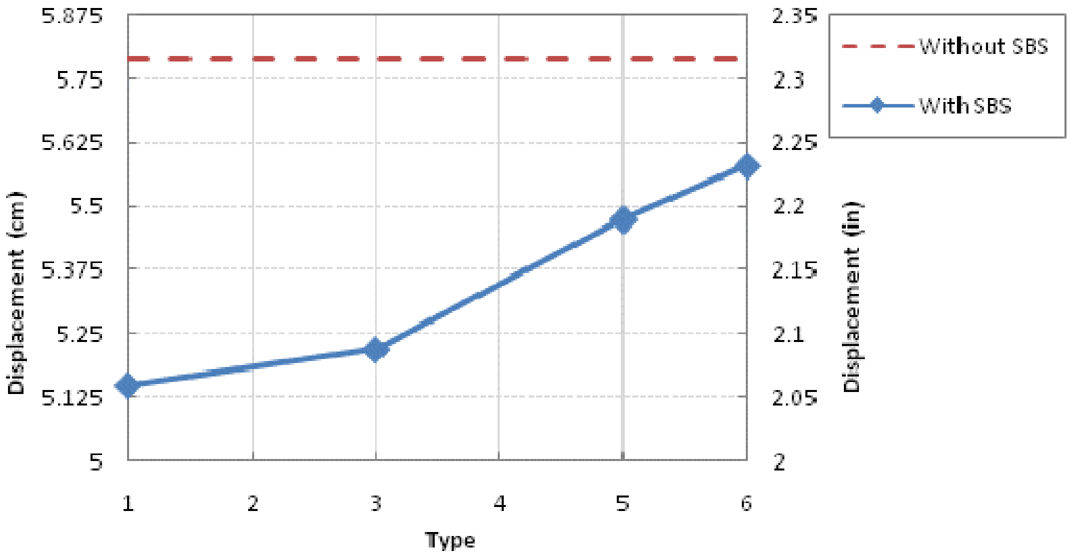


Fig. 144. Relative displacement of the left deck in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

Table 29
Shear force in the left abutment and central column in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

	Left Abutment		Central Bent, Central Column	
SBS	+X direction (kN)	-X direction (kN)	+X direction (kN)	-X direction (kN)
w/o SBS	521.3	-494.6	365.6	-403.9
1	637.8	-5146.3	443.5	-524.0
3	551.1	-3438.3	402.3	-541.3
5	531.1	-1249.4	389.1	-517.7
6	531.1	-882.5	374.7	-480.4

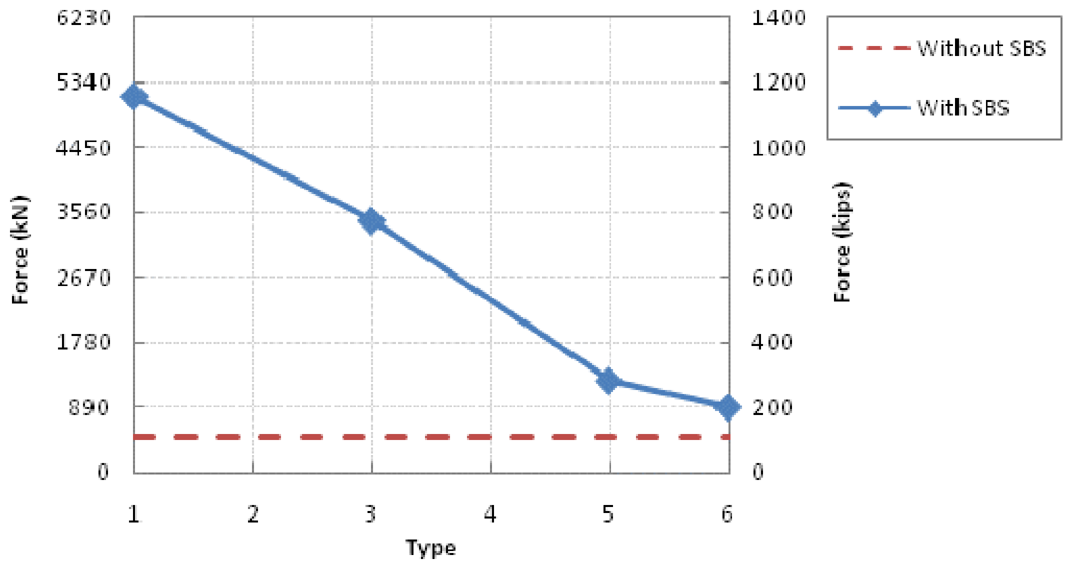


Fig. 145. Maximum shear force in the left abutment in the bridge equipped with various SBS with 5.08 cm (2 in) gap under a 0.43g ground motion.

4.2.2.4 Transverse deck movement

In this section, a two-span simply-supported bridge model is subjected to a 0.43g (Chi-Chi-N) ground motion acting in the transverse direction. The transverse movements of decks should be kept in a low range because the large relative movements between adjacent decks will result in damages to the expansion joints. In this model, two modeling cases with 2.54 cm (1 in) gap and 1.27 cm (0.5 in) gap in SBS respectively are conducted to investigate the performance of SBS for limiting deck movement in transverse direction.

For the bridge model without SBS, the deck movement in transverse direction under a 0.43g ground motion is shown in Fig. 146. For the bridge models equipped with

SBS having 1.27 cm (0.5 in) and 2.54 cm (1 in) gap, the deck movements are shown in Fig. 147 and Fig. 148. Fig. 149 and Fig. 150 are the load-deformation curves of the SBS at various locations with 1.27 cm (0.5 in) gap subjected to the 0.43g ground motion. Fig. 151 shows time history of shear force in left abutment for bridge without SBS. Fig. 152 and Fig. 153 are time histories of shear force in left abutment for bridges equipped with SBS (type1) and have 1.27 cm (0.5 in) and 2.54 cm (1 in) gap, respectively.

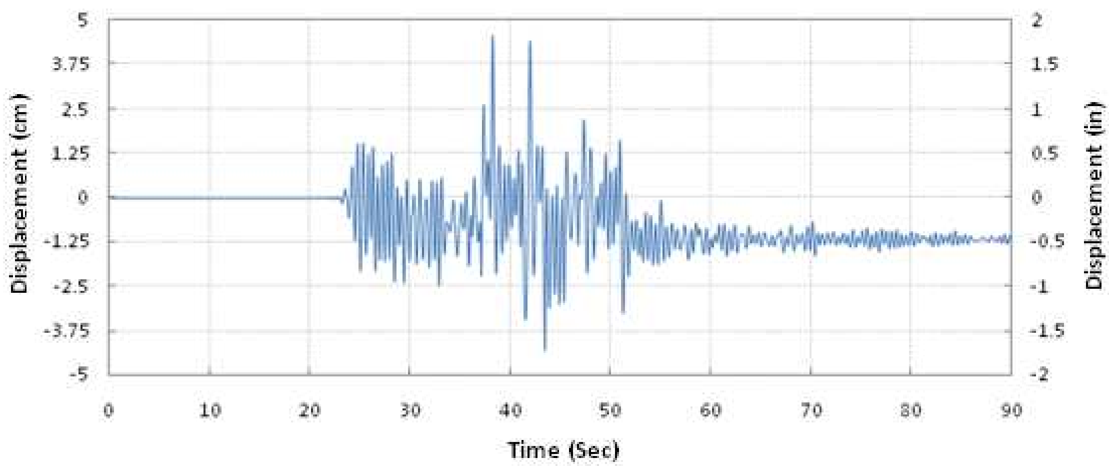


Fig. 146. Transverse displacement of the left deck in the bridge without SBS under a 1.01g ground motion.

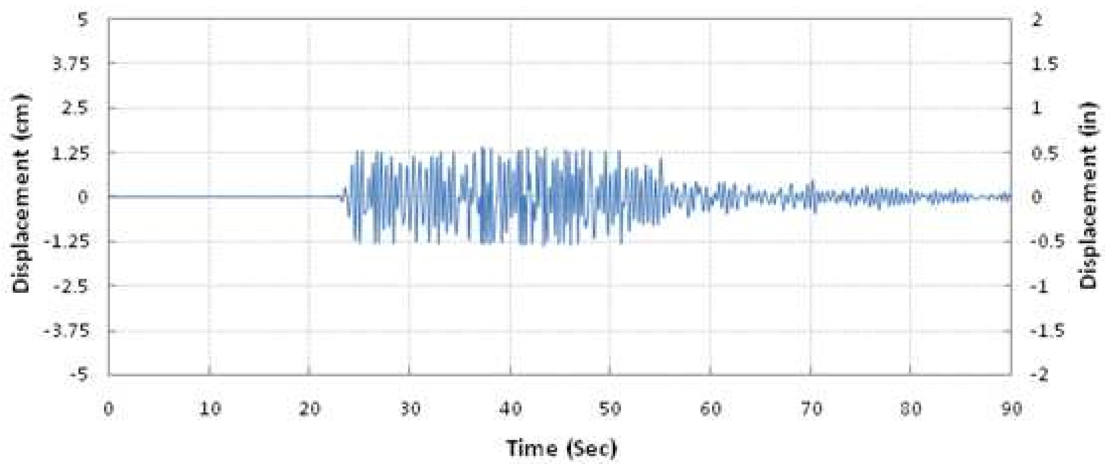


Fig. 147. Transverse displacement of the left deck in the bridge equipped with SBS (type1, 1.27 cm (0.5 in) gap) under a 0.43g ground motion.

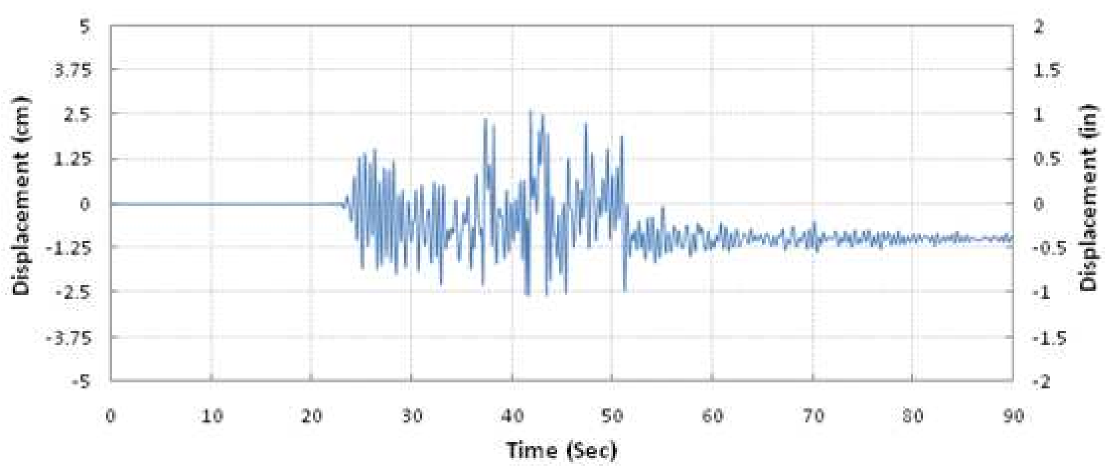
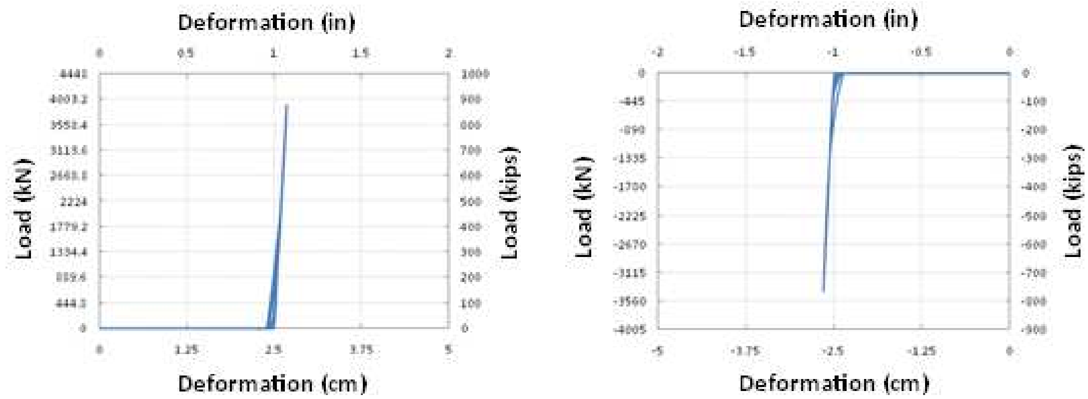


Fig. 148. Transverse displacement of the left deck in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.



(a) (b)

Fig. 149. Load-deformation relationship of the SBS (type1, 1.27 cm (0.5 in) gap) at the left end of the left deck under a 0.43g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

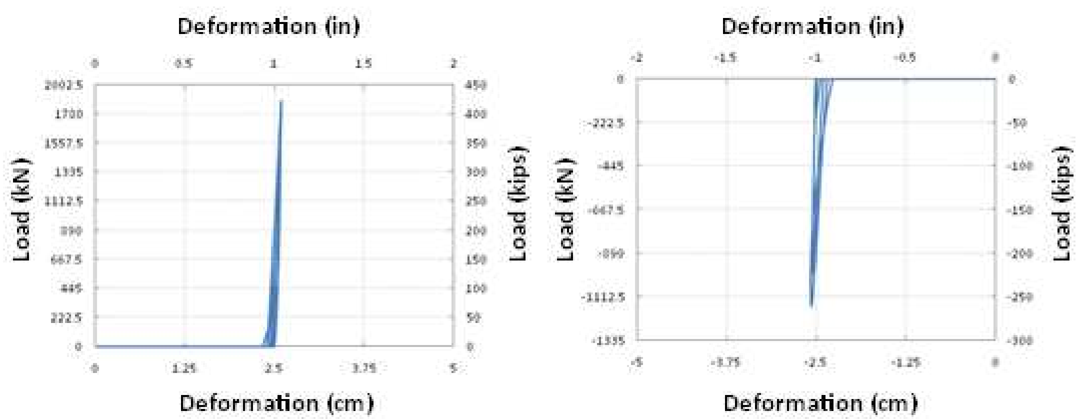


Fig. 150. Load-deformation relationship of the SBS (type1, 1.27 cm (0.5 in) gap) at the right end of the left deck under a 0.43g ground motion: (a) tensile member of the SBS, (b) compressive member of the SBS.

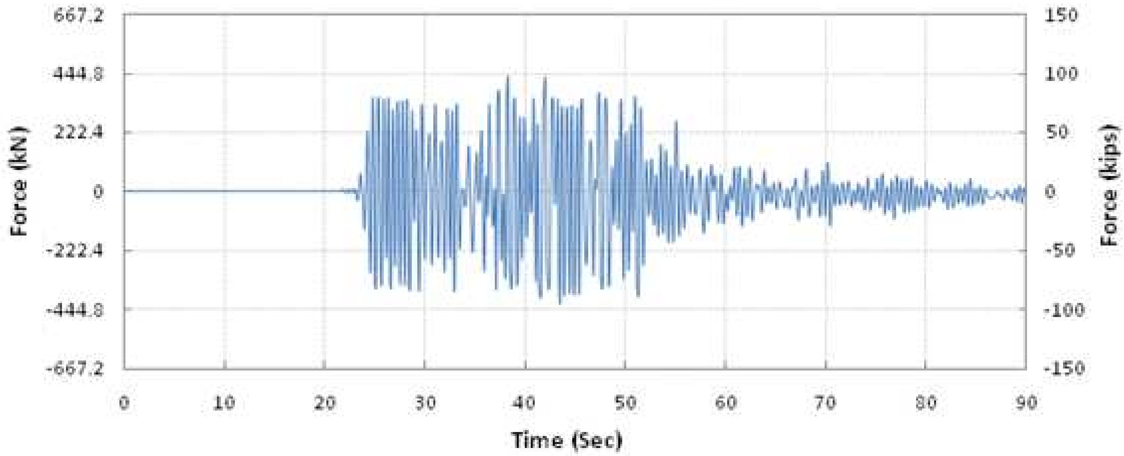


Fig. 151. Shear force in the left abutment in the bridge without SBS under a 0.43g ground motion.

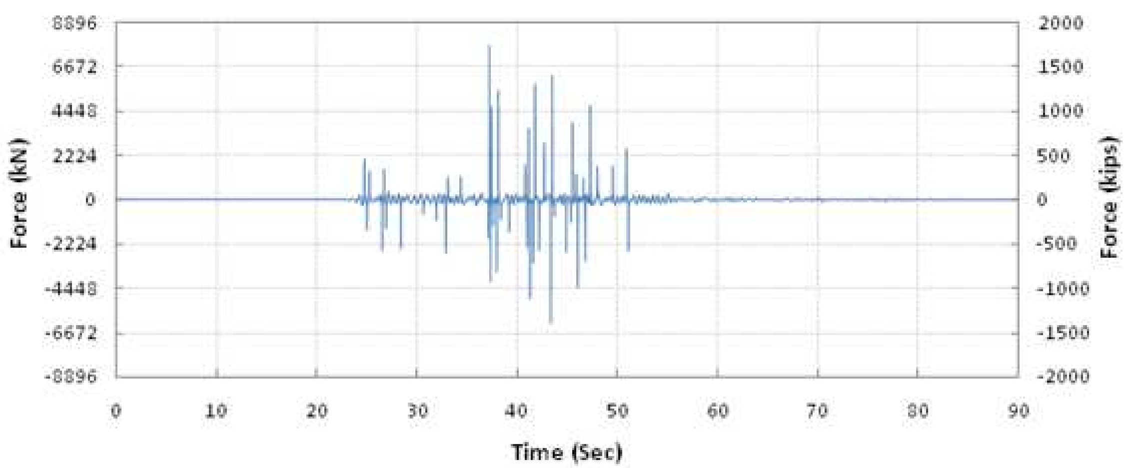


Fig. 152. Shear force in the left abutment in the bridge equipped with SBS (type1, 1.27 cm (0.5 in) gap) under a 0.43g ground motion.

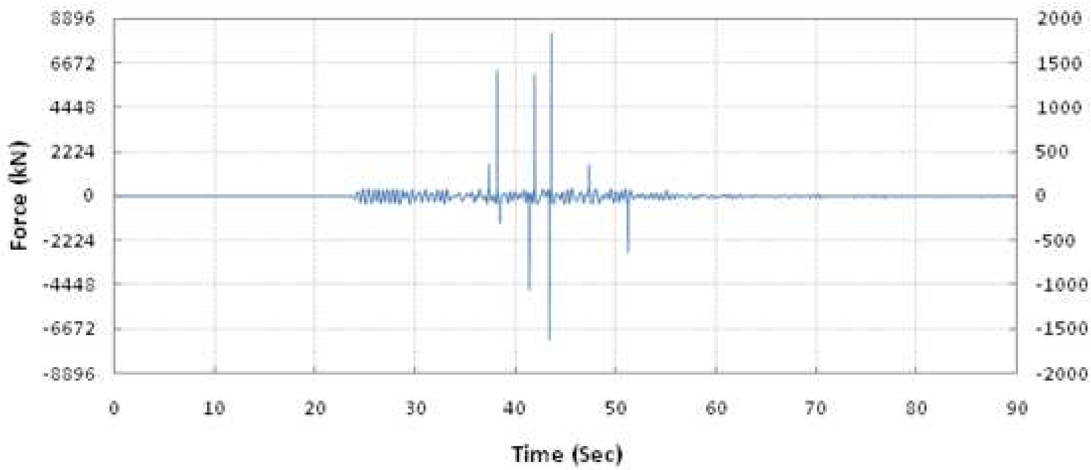


Fig. 153. Shear force in the left abutment in the bridge equipped with SBS (type1, 2.54 cm (1 in) gap) under a 0.43g ground motion.

4.2.3 Summary

The test results derived from the bridge models in previous sections are presented. These figures include deck displacement and shear forces in abutment and columns.

For the one-span, two-span and three-span simply-supported bridge, the summary of relative displacement of deck and maximum shear forces in the left abutment with all 6 various types of stoppers consider in this research are shown in Figures 154-159.

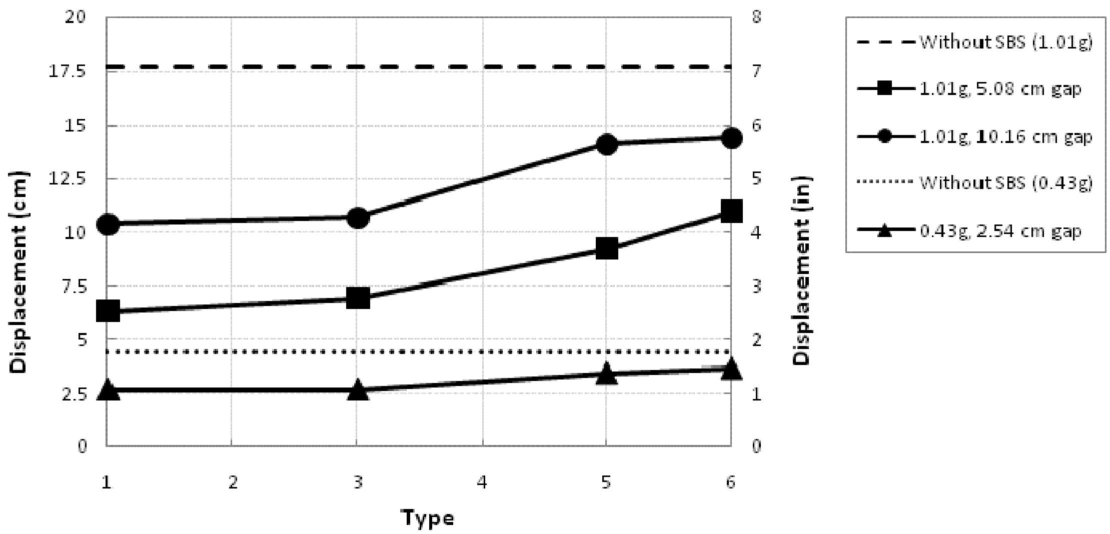


Fig. 154. Relative displacement of deck for one-span simply-supported bridges under 1.01g and 0.43g ground motion with various types of stoppers and different gap sizes.

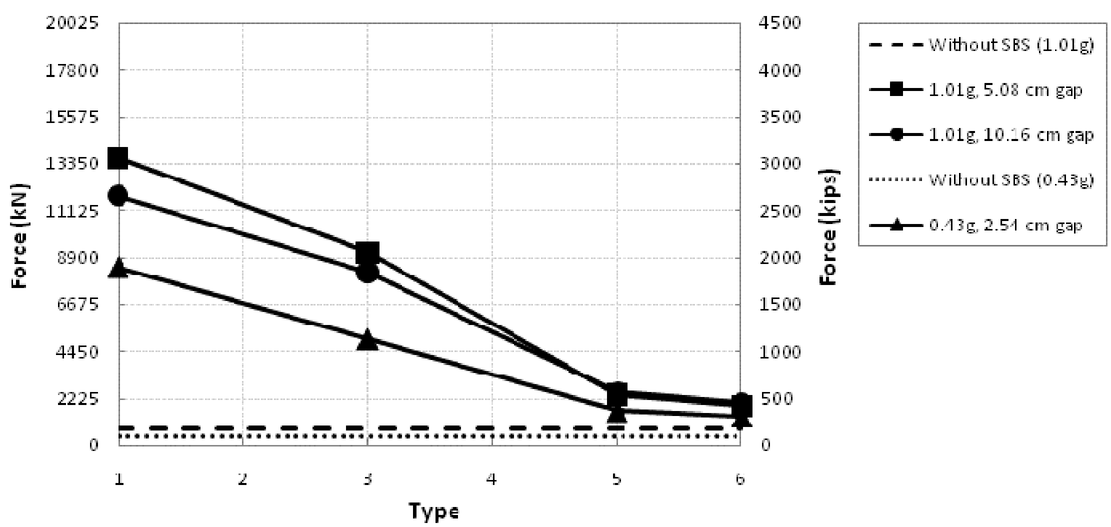


Fig. 155. Maximum shear force in left abutment for one-span simply-supported bridges under 1.01g and 0.43g ground motion with various types of stoppers and different gap sizes.

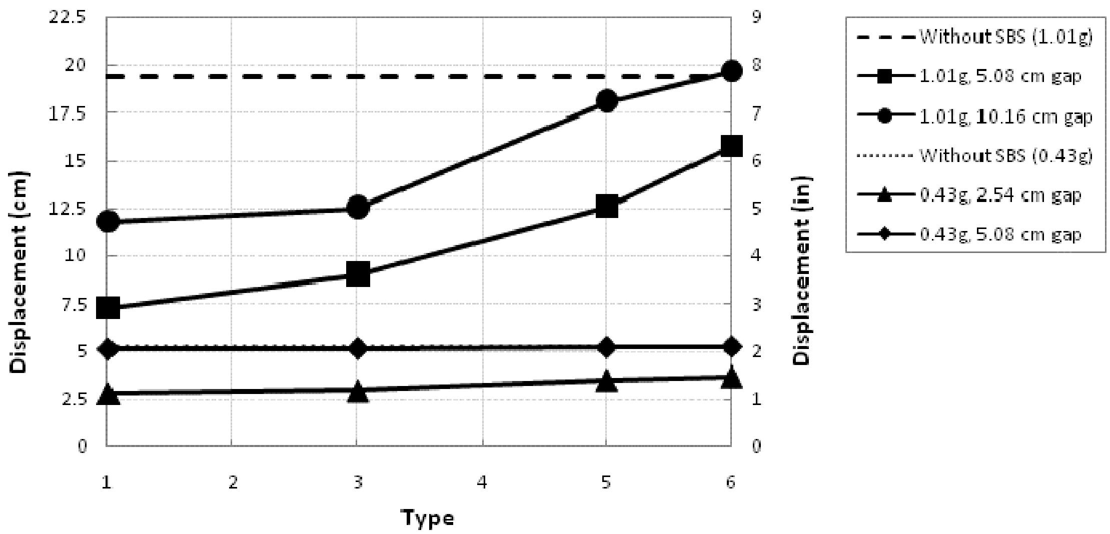


Fig. 156. Relative displacement of deck for two-span simply-supported bridges under 1.01g and 0.43g ground motion with various types of stoppers and different gap sizes.

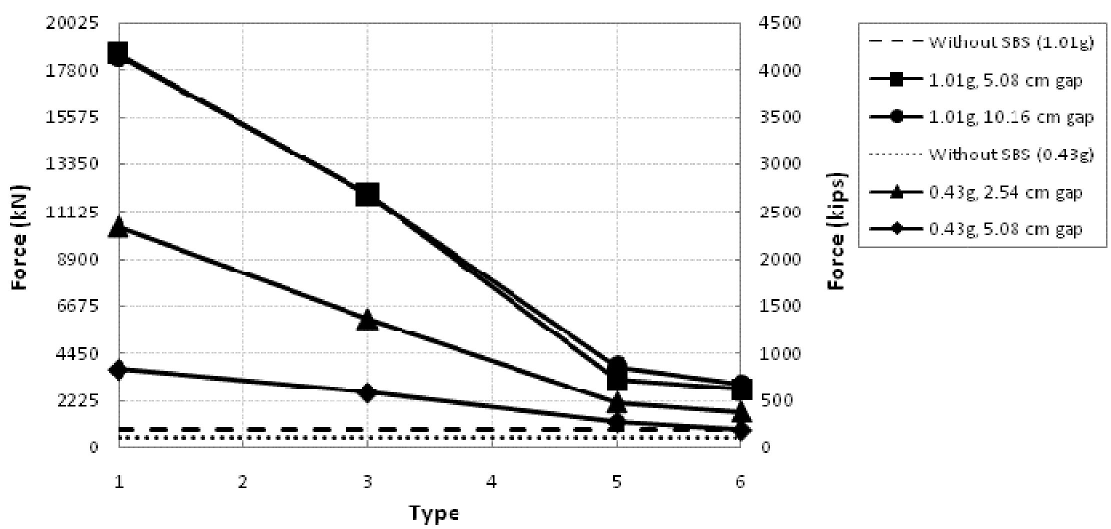


Fig. 157. Maximum shear force in left abutment for two-span simply-supported bridges under 1.01g and 0.43g ground motion with various types of stoppers and different gap sizes.

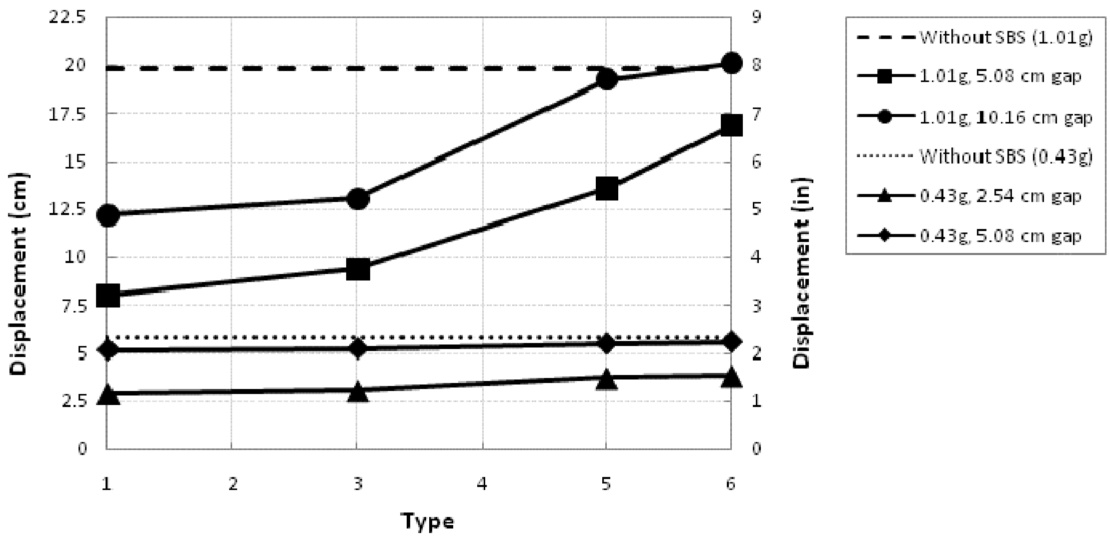


Fig. 158. Relative displacement of deck for three-span simply-supported bridges under 1.01g and 0.43g ground motion with various types of stoppers and different gap sizes.

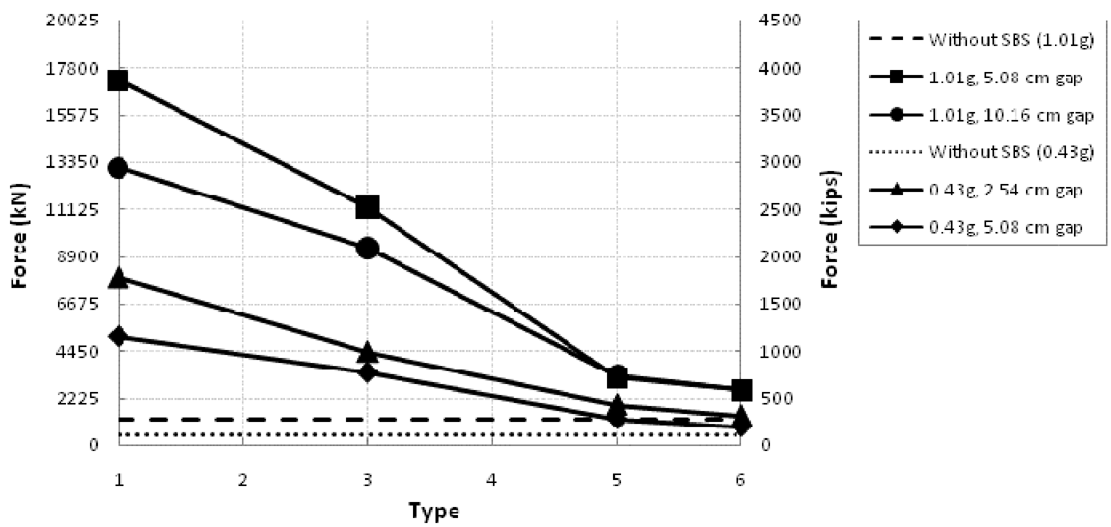


Fig. 159. Maximum shear force in left abutment for three-span simply-supported bridges under 1.01g and 0.43g ground motion with various types of stoppers and different gap sizes.

5. CONCLUSIONS

5.1 Discussion

Results from this research show how the SBS works conceptually. However, there are some practical issues that need to be considered in the SAP2000 modeling to reflect more realistic in-situ conditions since the existing model did not account for nonlinearity in the columns or site-specific soil properties for soil-structure interaction. As such, the forces obtained at the abutment for the type1 stopper are quite large, perhaps an upper bound. It may be anticipated that either the backwall of the abutment or the soil would fail before reaching such large shear forces reported. This restriction arises from the simplifying modeling assumptions adopted to represent the boundary conditions. It should also be noted that the 1999 Chi-Chi earthquake ground motion components used in this research are from a somewhat intense earthquake (estimated M_w=7.6 to M_w=7.7) with the epicenter located near the neighboring Shuangtung fault. As such, the modeling results obtained are not only reflective of the boundary conditions applied but also the frequency content of the input motion itself.

In addition, when a small gap, 5.08 cm (2 in) for example, is used in the SBS under a strong ground motion, the deck displacement will overcome the gap easily and result in a closed gap. After the gap is engaged, the abutment forces the deck to move simultaneously in the same direction until the abutment stops moving forward. Therefore, more force and energy will be transferred to the deck through the SBS, and the force required to stop the accelerated deck will be increased. Moreover, since the abutment is fixed in the model, the displacement of the abutment will be the same as the displacement of the ground without taking soil deformations into account. Also, the large forces generated by pounding in the SBS will not be limited by the force capacity of the backfill of the abutment. As such, a more definitive representation of the analytical bridge model should account for the following to better reflect in-situ conditions:

- First, the boundary conditions of the models in SAP2000 would need to be modified to reflect more realistic conditions so that the forces at the abutment are not so large. In this research, the abutments and columns are assumed to be fixed, and nonlinearity of the columns per the application of plastic hinge zones in the columns is not represented. Consequently, the large forces that are reported are transferred through the fixed end boundary conditions without taking into account representative soil stiffness values. In addition, the columns in the SAP2000 models are assumed elastic. Neglecting the nonlinearity of the columns will result in smaller displacements and larger forces given the lack of ductility in the columns as provided by the plastic hinges, which initiate the nonlinear response of the columns. In other words, more ductility in the columns is synonymous with more energy dissipation. With the columns modeled only as linear elements, energy will not be dissipated since plastic hinges do not exist in the columns.
- Second, when the forces obtained from the simulation are quite large, a weaker type of SBS should be used. The use of a weaker stopper can lower the force transferred

through the SBS and thus reduce large forces obtained at the abutments and columns. Although a weaker stopper can lower the force transferred, the plastic deformations in the weaker stopper will become larger. Therefore, the resulting larger deck displacement should be taken into account when determining the size of gap, G.

- Third, the forces obtained from the model should be checked for the constructability of the SBS. For example, large forces obtained at the abutment will increase the difficulty, and even make it impossible, to design the SBS. The connection of the deck component relies on bolts and shear studs. Large shear forces increase the required number of the bolts and shear studs, and increase difficulty to install them properly. From this research, assuming the shear force is equally resisted by the bolts and shear studs, 6672 kN (1500 kips) would require 22 bolts with diameters of 2.54 cm (1 in) and 6 shear rods with diameters of 3.81 cm (1.5 in) in the deck component. This would yield a specific layout of 11 bolts on each side of the girder and enhance the difficulty to install these bolts given limited space. However, a more reasonable specification would be to use the same diameter for both the shear rods and bolts. For example, using 3.81 cm (1.5 in) diameter shear rods and bolts would require 6 shear rods and 10 bolts in total, thus resulting in 5 bolts on each side of the girder. Therefore, similar calculations should be made to recommend a realistic number of bolts and shear rods required for construction as per the girder dimensions and for shear force resistance.

5.2 Summary

From this research, a new bearing system, referred to as the stopper-bearing system (SBS) was designed and calibrated based on analyses conducted in ABAQUS and SAP2000. According to the investigations conducted, the stopper-bearing system successfully decreases relative deck displacement to certain levels depending on the type of stopper applied. While future work is needed to enhance the analytical model to better reflect realistic in-situ bridge conditions and address some limitations of the existing analytical model, the following conclusions can be made based on the design process and simulation conducted in this research:

1. When designing the SBS, the stopper should be made to be the most flexible component such that major deformations on it are limited. The deck component and base component are much stronger than the stopper, and their deformations during pounding are negligible. Since major deformations locate mainly on the stopper, behavior of SBS can be adjusted by changing the properties of the stopper, such as increasing the strength of the stopper, etc. By adjusting the parameters, the performance of the system can be improved and predicted more accurately.
2. A stiffened stopper provides more reliable resistance than a square stopper and tapered stopper. Resistance of a stiffened stopper is mainly provided by its interior stiffeners; therefore, local damage at corners after pounding does not decrease its resistance significantly. Moreover, pounding of a stiffened stopper in the longitudinal direction does not inhibit its performance to resist lateral force from the transverse direction. Various resistance capacities of stoppers can be achieved

by adjusting the thickness of stiffeners and webs. After determining the properties of stopper, deck component and base component should be checked to make sure that they are stronger than the stopper.

3. For a one-span bridge under a strong ground motion of 1.01g with 10.16 cm (4 in) gap, the strongest stopper lowers the relative deck displacement from 18 cm (7.086 in) to 10.6 cm (4.154 in) but causes a maximum shear force of 11782.8 kN (2649 kips) in the abutment. In order to achieve best performance of the SBS, additional shear force transferred to the substructure should be taken into consideration. Given these large shear forces, retrofitting of the columns and foundations may be required. When retrofit of the columns is not applicable, the SBS equipped with a stopper with a smaller shear force capacity can be applied to meet the capacity of substructure and provide certain protection to the bridge. However, from previous case studies shown herein, the ability for limiting deck displacement will decrease accordingly. In this situation, the additional deck displacement should be taken into account as well.

4. Changing the size of the gap, G, between deck component and stopper is an alternative way to lower relative deck displacement and induce less additional shear force into substructure at the same time. This method induces large deformations in the stopper to stop the deck gradually rather than stop the deck immediately by providing high lateral resistance. Using a flexible stopper with smaller gap widths enables the contact between stopper and deck component to occur earlier, and smaller resistance can be provided gradually to stop the deck.

5.3 Recommendations for design and construction

When the preliminary design of the stopper-bearing system, the engineer first needs to determine what is the acceptable deck displacement range and the sizes of the bearings and bent cap. After these parameters are known, the dimensions of each component of the stopper-bearing system and the gap sizes, G, between stopper and deck component can then be determined. Another important factor that affects the design is the capacities of the columns and abutments. These capacities serve as guidelines for determining which type of stopper and deck component are appropriate. A recommendation for selecting the deck component is to make the deck component as strong as possible to avoid large plastic deformation occurs on it, and thus the performance of the SBS can be predicted precisely. While all necessary information are obtained, a computer simulation with a designated earthquake ground motion must be conducted to make sure the test results are satisfactory.

For the installation of the stopper-bearing system, the connection of the deck component and base component will greatly affect the stability of this system. To connect the deck component to the bottom of the concrete girder, the bottom surface of the concrete girder is expected to be drilled to make several holes for fitting the shear rods of the deck component (Fig. 11). In addition, one row of bolts is used to connect the deck component to the concrete girder from the sides. Therefore, it is necessary to make sure that it is acceptable to drill the concrete girder at the designated locations, and the drilled holes must be properly aligned to fit the shear rods on the deck component successfully. To connect the base component to the bent cap, the bolts and tendons are applied to make the base component as stable as possible. Like the deck component, several holes are required to be drilled on the top surface of the bent cap to fit the shear rod on the base component to provide reliable shear resistance. Therefore, it is necessary to drill these holes in the correct locations to fit the base component successfully. For the installation of the stopper, since performances in the longitudinal and transverse direction are different, it is important to install the stopper in the correct direction. For example, previous work done by Maleki [6] suggested that it is beneficial to use stronger side restrainers in the transverse direction to limit the transverse displacement of deck. A stopper design following this suggestion may make the stiffness of the stopper in the transverse direction stronger than the stiffness in the longitudinal direction. Therefore, the stopper must be correctly oriented to achieve expected performance.

5.4 Recommendations for future work

As noted in the discussion per Section 5.1, there are many ways to enhance the analytical bridge model itself to better capture the behavior of the SBS and bridge response. This section provides recommendations for future work to address those improvements and explore other important topics relevant to assessing the performance of the SBS as a practical solution for controlling bridge deck displacements. The following topics should be considered for future work:

1. Nonlinearity of the columns: The columns in this analysis are assumed elastic, therefore their nonlinear behavior is not represented. Nonlinearity of the columns will result in dissipation of energy and larger displacements of the decks. Therefore,

to obtain more precise and realistic results, the nonlinear behavior of the columns should be considered.

2. Soil conditions and soil-structure interaction: The abutments and columns in this analysis are fixed, and the soil properties are assumed infinitely stiff. To obtain better results, soil properties and the soil-structure interaction should be considered through the use of partial fixity constraints, which can be represented by translational and rotational springs with appropriate soil stiffness values.
3. Manufacturing: A prototype should be manufactured for experimental testing to validate the performance of SBS. Experimental testing is necessary to validate these results and support conclusions. Moreover, due to the intricacy of the SBS and precision required for construction, details of each component should be considered to account for manufacturing imperfections. In addition, lowering the manufacturing cost is another important goal for this system to be an economical option.
4. In order to get rapid take-up of this promising technology, it is necessary to minimize the unit cost of each SBS. One way to achieve this is to use cast iron and steel units. There should be designed and trial in comparison with units manufactured by welding steel plate components together.
5. Subject revised model to a suite of ground motions: To obtain better understanding of the performance of the SBS in different situations, a suite of ground motions need to be applied to the revised model. These ground motions help to understand the behavior of the SBS and the response of the bridge model due to various

earthquake events, where the results obtained from different situations can be studied.

6. Consideration of vertical acceleration: Vertical movement of deck caused by acceleration in the vertical direction will influence the performance of SBS because the contact area between stopper and deck component may change. Different contact area provides different resistance. When the deck moves upward, the contact area would decrease, and less resistance would be provided by the stopper. When the deck moves downward, the contact area increases and more resistance will be provided.
7. Consideration of various material properties for SBS: The stopper, deck component, and base component were initially designed and analyzed based on a yield strength of steel of 60ksi. To limit major deformation in the stopper, the deck component and base component should be much stronger than stopper. Therefore, these two components require high strength and stiffness to avoid large deformation in them. By using higher strength material in these two components, their stiffness and strength will increase and their dimensions will decrease. In different situations and designs, the stopper may require high strength to have better efficiency or low strength to limit forces transferred. To meet various needs, using different material properties together with adjusting thickness of stiffeners and webs will be an effective in optimizing the expected performance of the SBS.
8. SBS design methodology for practitioners: To streamline the rigorous analysis process required for design of the SBS, a simplified design methodology for

practitioners based on an energy approach and structural mechanics is needed. This methodology can be modified once the SBS has been validated experimentally, where the experimental results will complement structural theory. Appropriate correction or overstrength factors can then be applied to equations in the design methodology, similar to existing design methods for bearings as noted in the AASHTO LRFD Bridge Design Specifications (2007) [10], so that practitioners can determine the feasibility of using the SBS to retrofit a bridge.

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VITA

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