STUDY ON APPLICATION OF ENERGY-DISSIPATING SACRIFICIAL DEVICE (EDSD) FOR ENHANCING SEISMIC PERFORMANCE OF GIRDER BRIDGES

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ABSTRACT

A new Energy-Dissipating Sacrificial Device (EDSD) is developed for steel plate girders, which can effectively dissipate the energy stored in the structures during seismic actions. A simplified bridge analysis method is utilized first to see the effectiveness of the EDSD, and then using a commercial FEM program, the seismic performance of the device is examined on the whole bridge system. To verify the performance of the EDSD, various seismic responses of a sample bridge with the EDSD are analyzed in terms of energy, member forces and deformation. The full scale model tests are conducted to certify the performance of the EDSD when it is applied on existing bridges. The results show that the proposed EDSD under seismic excitations can significantly decrease the energy stored in the bridge structures and reduce the relative displacements of each superstructure to the ground. The EDSD is also found to function as a structural fuse under strong ground motions, sacrificing itself to absorb the excessive energy. Consequently, economical enhancement of the seismic performance of bridges can be achieved by employing the newly developed energy-dissipating sacrificial device.

Keywords: EDSD, retrofit, energy-dissipating device, seismic loads

INTRODUCTION

Various new innovative devices based on ductile design concept have been developed as solutions to enhance seismic performances of new or existing bridges (ATC, 1983; Buckle et al. 1986; SED, 1993; Shirole and Malik, 1993). They can be categorized into three broad areas such as the base isolation, active control and passive energy dissipation systems. The base isolation and active control systems are highly effective means for enhancing structural functionality and safety, but the high cost of installations and maintenances considering Life Cycle Cost (LCC) might be an economical burden in weak and moderate seismic regions.

On the contrary, passive energy dissipation systems are relatively low-cost, and can be used both for seismic damage mitigation and for rehabilitation of aging or deficient structures (Soong and Spencer, 2002). These systems dissipate energy through simple structural behaviors, such as frictional sliding, metal yielding, and phase transformation in metals without any expensive control systems or sensors. This gives economical advantages for moderate seismic regions and it means that passive energy...
dissipation systems might be relatively proper method for the region where the possibility of seismic occurrence is not quite high.

Eccentrically Braced Frames (EBF), Shear Panel Systems (SPS), and Triangular-plate Added Damping and Stiffness Devices (TADAS) are examples of the most recent passive energy dissipation systems which are using ductile end-diaphragms for seismic retrofit of steel girder bridges. The ductile end-diaphragms are designed to show plastic behaviors before pier structures are damaged under seismic excitation. However, each of these devices works only in transversal direction of a bridge and has no capacity to dissipate energy in longitudinal direction of a bridge (Zharai and Bruneau, 1999; Bruneau et al. 2002).

In this study, a new Energy-Dissipating Sacrificial Device (EDSD) is proposed, which can effectively dissipate the energy stored in the major members, such as piers in bridges, due to the longitudinal seismic excitations. Also, the mathematical bridge model is developed to analyze seismic performance of a bridge with the EDSD. The seismic performance enhancement due to the application of EDSD is examined by comparing hysteretic energy of piers on relative energy theory.

The EDSD is composed of restraining devices and sacrificial members, which are selected among the secondary members, such as the end sway bracing. To make EDSD as an effective method for enhancement of seismic performance, the following characteristics are required. 1) EDSD prevents severe damage of major members such as girders or piers by dissipating excessively stored energy through repeated plastic behavior of sacrificial members. 2) The EDSD has simple installation procedure and can be easily replaced after damage. 3) The EDSD should not require the expensive cost for installation and maintenance during a bridge service life.

COMPONENTS AND BEHAVIOR OF EDSD

In this study, the EDSD is developed firstly for steel plate girder bridges widely used on a middle-size river in Korea. Fig. 1 shows one example of EDSD applied at a steel plate girder bridge. As shown in Fig. 1, the EDSD is composed of a ductile vertical bracing (sacrificial member) and a displacement restrainer (restraining device) for both longitudinal and transverse direction. A vertical end bracing of a bridge is designed to have a role of an energy-dissipating device by repeated nonlinear flexural behavior. A restraining device has relatively large stiffness and it is fixed on the top of a pier or an abutment. Also, a restraining device will not cause any plastic behavior of a vertical bracing for the small deformation due to the temperature change because of the designed initial gap distance between a restrainer and a bracing. This initial gap distance makes EDSD to activate only when the relative distance between a main girder and an adjacent substructure is larger than initial gap distance. This behavior can be simplified as a fixed-end supported beam with initial gap distance shown as Fig. 2, and can be represented by a simplified model, which has nonlinear spring elements with initial gap distance in both directions as shown in Fig. 3.

Figure 1. EDSD Applied at a steel plate girder bridge.
The bi-linear hysteretic model with initial gap distance \( (d_{\text{gap}}) \) and stiffness \( (k) \) in both directions is shown in Fig. 4, and can be described as follows.

\[
P = \begin{cases} 
  k(\delta_r - d_{\text{gap}}) & (|\delta_r - d_{\text{gap}}| > 0) \\
  0 & (|\delta_r - d_{\text{gap}}| \leq 0)
\end{cases}
\]  

PRELIMINARY ANALYSIS BY USING THE SIMPLIFIED BRIDGE MODEL

This study analyzes firstly the energy-dissipating capacity of EDSD and its effects on seismic responses of a simple structure by using the simplified bridge analysis model. Energy responses and displacement responses are examined to certify enhancement of seismic performance. Energy responses are total input energy, hysteretic energy of EDSD and piers, and damping energy. Displacement responses are relative displacement against ground motions. Total input energy \( (E'_i) \) of a bridge structure due to the seismic excitations can be expressed as follows (Bruneau and Wang, 1996).

\[
E'_i = E'_k + E'_\xi + E_a = E'_k + E'_\xi + E_s + E_h
\]  

where \( E'_k \), \( E'_\xi \) and \( E_a \) are the relative kinetic energy, damping energy, and energy absorbed in the structure, respectively. \( E_a \) is composed of recoverable elastic strain energy, \( E_s \) and irrecoverable hysteretic energy, \( E_h \).

A Sample Bridge and Corresponding Simplified Mathematical Model

Fig. 5 shows the configuration of the considered sample bridge, which is designed according to the Korean Design Codes for Highway Bridges (2005) as a purpose of simulation only and each component has minimal safety factor. The corresponding simplified mathematical model is
represented in Fig. 6, and this model can consider the effects of the friction force at a movable support, the nonlinear behavior of piers, and the translational and rotational motions of foundations (Kim et al., 1999).

![Figure 5. Configuration of a considering bridge.](image)

(a) Plan view  (b) Cross section (unit: mm)

Figure 5. Configuration of a considering bridge.

![Figure 6. Simplified mathematical model with multi degrees of freedom.](image)

(a) Without EDSD  (b) With EDSD

Figure 6. Simplified mathematical model with multi degrees of freedom.

**Energy and Displacement Response of the Sample Bridge**

Using SIMQKE code (Vanmarcke and Gasparini, 1976), 10 artificial ground motions are generated for each PGA from 0.1g to 0.5g, which are compatible to the design spectrum of Korean Design Codes for Highway Bridges (2000) for the seismic analysis of this section. The properties of a sacrificial member and initial gap distance of the EDSD are designed as minimum dimensions provided with Korean Design Codes for Highway Bridges (2000). A sacrificial member is selected as a 75mm×75mm rectangular shape member with 10mm thickness, and the initial gap distance is set as 4cm.

Without EDSD, most of input energy is dissipated by hysteretic energy of piers as shown in Fig. 7(a). With EDSD, large portions of input energy (about 40% of hysteretic energy of piers) are dissipated as shown in Fig. 7(b). The little difference of total input energy is because it is changed according to the stiffness of structure under the relative energy equilibrium equation (Uang and Bertero, 1990; Bruneau and Wang, 1996).

Table 1 shows the mean values of the ratio of hysteretic energy to total input energy. The EDSD reduces the hysteretic energy of pier up to 44% (PGA=0.3g) and is relatively more effective at the range of PGA 0.2g~0.4g than other PGA ranges. It is because the response under PGA 0.1g is not large enough to activate the EDSD frequently, and because the failure of a sacrificial member occurs during energy dissipation process under PGA 0.5g (Fig. 8).
Figure 7. Total input energy history with and without EDSD (PGA=0.3g).

Table 1. Hysteretic energy ratio to total input energy with EDSD

<table>
<thead>
<tr>
<th>PGA</th>
<th>0.1g</th>
<th>0.2g</th>
<th>0.3g</th>
<th>0.4g</th>
<th>0.5g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without EDSD</td>
<td>0.83</td>
<td>0.83</td>
<td>0.86</td>
<td>0.90</td>
<td>0.92</td>
</tr>
<tr>
<td>With EDSD</td>
<td>0.66</td>
<td>0.51</td>
<td>0.48</td>
<td>0.52</td>
<td>0.65</td>
</tr>
<tr>
<td>Decreasing Ratio</td>
<td>21.0%</td>
<td>38.6%</td>
<td>44.2%</td>
<td>42.2%</td>
<td>29.3%</td>
</tr>
</tbody>
</table>

Figure 8. Force of EDSD (PGA=0.5g).

Fig. 9 shows the time histories of relative displacement between ground and P1 pier under PGA 0.2g and 0.3g. The EDSD restrains the displacement of each vibration unit, and results in decrease of relative response displacement. In case of PGA 0.2g, the maximum relative displacement is reduced from 9.4cm to 8.3cm. In case of PGA 0.3g, it is reduced from 14.6cm to 11.9cm. These results can be explained by not only the restrains effect but also the force-redistribution effect of the EDSD. The EDSD effectively redistributes inertia force of super-structure to the adjacent P2 pier and reduce the force of P1 pier.

Figure 9. Time histories of relative displacement between ground and P1 pier with EDSD.
The mean values of the maximum relative displacements between ground and P1 pier are listed in Table 2, as results of simulations with 10 ground motions for each PGA. Large decreasing of maximum relative displacements is obtained by application of the EDSD, and this decreasing rate becomes larger with increasing PGA. On the contrary, this decreasing rate is dropped when PGA is larger than 0.5g, and it is because failure of a sacrificial member. Although the sacrificial member reaches at failure state, before failure it still has significant role of dissipating large energy that is generated at early stage of seismic excitation.

<table>
<thead>
<tr>
<th>PGA</th>
<th>0.1g</th>
<th>0.2g</th>
<th>0.3g</th>
<th>0.4g</th>
<th>0.5g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without EDSD</td>
<td>4.96</td>
<td>10.03</td>
<td>15.66</td>
<td>23.88</td>
<td>35.65</td>
</tr>
<tr>
<td>With EDSD</td>
<td>4.39</td>
<td>8.44</td>
<td>13.05</td>
<td>18.14</td>
<td>28.76</td>
</tr>
<tr>
<td>Decreasing Ratio</td>
<td>11.5%</td>
<td>15.9%</td>
<td>16.7%</td>
<td>24.0%</td>
<td>19.3%</td>
</tr>
</tbody>
</table>

FULL SCALE PSEUDO-DYNAMIC TESTS FOR SEISMIC PERFORMANCE OF EDSD

KISTC (Korea Infrastructure Safety and Technology Corporation) strongly recommends that the energy-dissipating device, such as EDSD, developed for enhancing seismic performances of bridges should be tested to verify its performance and safety before practical application (2004). In this study, therefore, the EDSD tested to evaluate its energy-dissipating performance and estimate the safety of connection between the sacrificial device and the girder of the bridge. A simple modeling and analysis process need to be developed, moreover, to design the EDSD easily for application of itself to any structures.

The full scale models composed of EDSD and partial bridge referred just in front of this section are prepared. Corresponding pseudo dynamic tests are conducted to investigate the ductile behavior of sacrificial members and stress level of plates connecting a sacrificial member and a girder of bridge. The specimen, that is end part of the steel plate girder bridge, is fixed to bases, and then load increased gradually is applied by the actuator machine the restraining device is attached to, as shown in Fig. 10.

Fig. 11 shows hysteretic curve of sacrificial members obtained from the experimental data with and without the gap between the restrainer and the bracing. According to the result, the actual stiffness of sacrificial members is slightly larger than the stiffness calculated through the theory. It is because the cross section of the sacrificial member is increased by welding process and attached stiffeners. In order to apply more practical hysteretic model of the sacrificial member in the following seismic analysis, the stiffness and the hysteretic curves of the sacrificial member are corrected based on the test results. Fig. 12 shows the hysteretic curves of sacrificial devices obtained by the mathematical analysis using corrected hysteretic model, which will be used in the numerical simulations.
The maximum stress of plates connecting a sacrificial device and a girder of bridge appears as 1124kgf/cm² that is less than the allowable stress of 1400kgf/cm². It means connecting parts are safe during the EDSD dissipates the seismic energy of the structure.

**SEISMIC RESPONSE OF THE PSC GIRDER BRIDGE WITH APPLICATION OF EDSD**

Seismic responses of a whole bridge system are examined using a commercial FEM analysis program (SAP2000) so that engineers are able to utilize EDSD in practical bridge design. Through 3-dimensional analysis of a bridge with various values of number, applied locations and stiffness of EDSD, the optimum design of EDSD may be possible with consideration of some limitation occurring in setting up the EDSD.

A PSC girder bridge actually designed to be in service which needs seismic retrofit is chosen and shown in Fig. 13. The modeling and analysis method using SAP2000 have been verified in the preliminary study by comparing results with those from numerical method and it shows good agreement. The second segment of the bridge from pier P2 to P5 was selected for seismic analysis and EDSD are applied between every neighboring girder on P2, P4 and P5 longitudinally movable bearing installed at, as shown in Fig. 14. To find the optimum stiffness of sacrificial members of each EDSD, the variation of hysteretic energy of each EDSD with various stiffness values of sacrificial members is generated as shown Fig. 15. Stiffness of sacrificial members of EDSD1, EDSD2 and EDSD3 are determined so that the amount of seismic energy dissipation would be maximized. The initial gap distances are set as 2cm for EDSD1 and EDSD 2 and 3cm for EDSD3.
Table 3 shows the mean values of the maximum relative displacement between superstructure and P2, P4 and P5 respectively under PGA 0.154g, 0.2g and 0.3g. Overall, the maximum relative displacement decreased by more than 60% under not only 0.154g, that is design ground acceleration of this bridge, but also 0.2g and 0.3g.

Table 4 shows the mean values of the maximum shear force of piers under PGA 0.154g, 0.2g and 0.3g. Overall, the maximum shear force of P3 longitudinally fixed bearings are installed at is decreased and that of P2, P3 or P5 is increased. This result reveals the force-redistribution effect of the EDSD clearly. Especially, the providing capacity of P3 evaluated from the process represented in “Guide for Evaluation and Improvement of Seismic Performance of Existing Bridges (KISTC, 2004)” is 475tonf; it is smaller than the required capacity of 511tonf before application of the EDSD. However, after application of EDSD, the required capacity of P3 is reduced to 222tonf, and it means P3 pier becomes safe under the design earthquake.
Table 3. Maximum relative displacement between superstructure and piers with and without EDSD (unit: cm)

<table>
<thead>
<tr>
<th>PGA</th>
<th>Without EDSD</th>
<th>With EDSD</th>
<th>Decreasing Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S-P2</td>
<td>S-P4</td>
<td>S-P5</td>
</tr>
<tr>
<td>0.154g</td>
<td>6.75</td>
<td>6.90</td>
<td>6.73</td>
</tr>
<tr>
<td>0.2g</td>
<td>8.73</td>
<td>9.86</td>
<td>8.91</td>
</tr>
<tr>
<td>0.3g</td>
<td>13.10</td>
<td>14.79</td>
<td>13.36</td>
</tr>
</tbody>
</table>

Table 4. Maximum lateral force of piers (unit: tonf)

<table>
<thead>
<tr>
<th>PGA</th>
<th>Without EDSD</th>
<th>With EDSD</th>
<th>Decreasing Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P2</td>
<td>P3</td>
<td>P4</td>
</tr>
<tr>
<td>0.154g</td>
<td>56</td>
<td>511</td>
<td>124</td>
</tr>
<tr>
<td>0.2g</td>
<td>78</td>
<td>654</td>
<td>151</td>
</tr>
<tr>
<td>0.3g</td>
<td>117</td>
<td>982</td>
<td>227</td>
</tr>
</tbody>
</table>

CONCLUSIONS

An energy-Dissipating Sacrificial Device (EDSD) is proposed as a solution for enhancement of seismic performance of a bridge, which is designed to dissipate excessive energy stored in piers. A simplified mathematical bridge model with EDSD is developed and various ground motions are applied to analyze energy dissipating capacity and enhancement of bridge seismic performance. Analysis of energy responses and displacement responses are performed for more quantitative evaluations. With full size specimen, pseudo dynamic tests are conducted to see the dissipation capacity of the EDSD, and also to obtain the more practical stiffness and the hysteresis curves for the further numerical simulations. The seismic responses of a whole bridge system with the EDSD are also evaluated to determine the optimal design of EDSD by examining various ways of application of the EDSD. The proposed EDSD under seismic excitations can significantly decrease the hysteretic energy of the piers and reduce the relative motions in bridges. In addition, the EDSD is found to function as a structural fuse under strong ground motions, sacrificing itself to absorb the excessive energy with application to the bridge in service. Employment of EDSD can be a possible solution for economical enhancement of seismic performance.

REFERENCES


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