Numerical Performance of Energy Dissipation Slotted Plate for Bridge Unseating Prevention

Mustafa Kareem Hamzah¹, Farzad Hejazi²

¹Department of Civil Engineering, University of Warith Al-Anbiyaa, Karbala 56001, Iraq
²Department of Civil Engineering, University Putra Malaysia, 43400, Malaysia.

Email: Mustafahamzah1989@gmail.com

Abstract. Recently, the bridge unseating prevention devices are widely used in active seismic zones. These devices are stiffness dependant, velocity dependant and energy dissipation devices. The energy dissipation devices are designed to overcome the energy that transfers from bridge substructure to superstructure. However, the current devices are not controlled to function with different ground motion intensities and should be replaced after yielding. Therefore, this research introduced a slotted plate energy dissipation device with three parts, each part function in known deformation range. The slotted plate behavior has been evaluated numerically by finite element method. Displacement control and load control analysis has been done, and then the effect of steel grade is studied to predict the suitable steel properties for designing the plate. Moreover, the slotted plate behavior is applied in 3D bridge seismic analysis to assess the multi-level performance and the ability to overcome the seismic effect on the bridge in longitudinal direction. The results approved the capability of the plate to dissipate energy in multi-stage of deformation. The lower steel grade is suitable for low to moderate earthquake zone and the high grade can be used in severe ground motion areas. Furthermore, the bridge longitudinal behavior has enhanced with different steel grades of the slotted plate.

Keywords: slotted plate, multi-level, bridge unseating, energy dissipation, numerical performance

1. Introduction

The severe effect of earthquake on short span bridges structural performance has been noticed during the recent seismic events [1-3]. The girder failing-off is the result transferring the earthquake energy from substructure to girders and failure of bearing [4]. Therefore, the researchers figured out the need for enhancement of bridge seismic performance by proposing internal technologies such as built-in pipe dampers [5, 6]. However, external technologies are more widely used to overcome bridge unseating and they can be stiffness dependant, velocity dependant and energy absorption devices [7-9]. The yielding dampers are the most widely used devices since they are cost effective, simple structure, dissipate ground motion energy and the material is available [10]. Mohammadi et al. (2017) proposed Triangular Plate Dampers for large deformation. Numerical Monotonic loading has been applied on the damper for plate performance assessment. Furthermore, the plate was attached to frame structure and 12 scaled ground motion applied. The researchers introduced a method to determine the hole dimension in the damper [11]. Chan et al. (2013) performed experimental and numerical study to evaluate the cyclic performance and energy dissipation capacity of yielding shear panel. Cyclic testing was performed on both perforated
and un-perforated specimens. The outcome approved that the perforated decreased stiffness and strength [12]. Zahrai (2017) conducted a nonlinear finite element analysis on building equipped with multi-level pipe damper. The output demonstrated that damper comprehensively mitigated the severe effect of ground motion [13].

Vasseghi (2011) introduced a cost-effective shear key to mitigate the impact of ground motion in transverse direction in precast concrete girder bridges. Experimental study was performed on the shear key to assess the cyclic response and nonlinear analysis was conducted to predict the numerical behavior of the bridge that equipped with the damper. The results explained the superior behavior of the shear key by dissipating energy ductility. In addition, the bridge seismic performance has been enhanced [14]. Peng (2014) developed a yielding damped with vertical free mechanism in order to achieve large deformation capacity. Deng (2014) proposed a metallic damper that functions in longitudinal and transverse directions in bridges. Both studies examined the performance of dampers experimentally and numerically and concluded the comprehensive behavior of the energy dissipation devices [15, 16]. Zhou (2019) evaluated the seismic performance of long span bridge equipped with metallic damper experimentally and numerically and approved the superior performance of bridge with the damper [17]. However, the current technologies are not controlled to function with different seismic excitation intensities and should be replaced after yielding. Therefore, this research proposed a slotted plate energy dissipation device that shows multi-level performance with different earthquake intensities. The plate performance is assessed numerically in terms of load displacement and energy dissipation capacity. Additionally, bridge seismic performance with the slotted plate is estimated.

2. Slotted plate

The slotted plate is a type of metallic damper that provide large deformation with adequate energy dissipation capability. In this study, the performance of simple slotted plate that formed as pipe is evaluated to assist in the plate shape selection in the proposed damper. Figure 1 shows the slotted pipe that assessed numerically. The length is 0.9m and the diameter was about 100mm, the thickness tested to be 8mm and 10mm in order to measure the thickness effect on the plate performance. The slots were considered with 5mm hole and 50mm distance between each slot. The numerical behavior of the plate is evaluated using finite element software, the concept of symmetry is utilized to simplify the evaluation process and save time. The plate steel elastic properties were 200GPa elastic modulus and 0.3 Poisson's ratio. In terms of plasticity, the steel yielding stress is 400 MPa. The plate is fixed from one end and 200mm displacement is applied in the other end.

![Figure 1 slotted plate sample (cylindrical shape).](image-url)

The deformation, yielding, and stresses distributions are shown in Figure 2. Large deformation is demonstrated with comprehensive resistance. The maximum stresses are located around the slots exhibiting yielding of almost all the plate except the two ends. The AC yield is another
factor that measures the yielding of the plate. AC yield explained that the specimen cross over the yielding and mostly reached to the ultimate capacity.

![Figure 2](image)

**Figure 2** Deformation, stresses and yielding of slotted pipe.

The load displacement curves of both thicknesses of plate are shown in Figure 3. For plate with 8mm, the maximum capacity was less than 160KN when the displacement reached to 200mm. However, the resistance of 10mm thickness plate is about 174KN indicating that the thickness has slightly impact on the overall performance. When the displacement reached to less than 10mm the yielding was happened and the resistance was more than 50KN for 8mm plate. But the resistance was more than 120KN and displacement around 25mm when the yielding occurred for the 10mm plate.

![Figure 3](image)

**Figure 3** Load displacement curves of different thicknesses of slotted pipe.

The results demonstrated that using 10mm plate is more suitable than 8mm for development of the energy dissipation plate. In addition, the plate with circular cross section is not suitable for limiting the movement since it's provided large displacement than not preferred in bridge unseating case. Therefore, this study considered the rectangular shape plate to propose the device.

### 3. The proposed energy dissipation device and numerical assessment

Due to the severe impact of seismic excitations on bridges, it's essential to provide simple solution that provide resistance, energy dissipation and unseating prevention. Thus, this study proposed a multi-level energy dissipation slotted plate. The plate dimensional characteristics and attachment to the bridge are demonstrated in Figure 4. The overall dimensions of the device are 400,100, 50mm. The device consists of multi layers of slotted plate that attached one over each other. From one end all the plates are same configurations, but the other end provided with
different configuration to fulfill the desired performance. The thicknesses of the inner to outer plate were 10, 10, 6mm. The slots were 5mm hole each 45mm. In order to get the multi-level performance, the inner plate linked directly to connection plate that will be attached to the bridge bent or abutment. However, the other side is attached to the bridge girder. All the plates are linked together and connected to the girder by L-shape connection.

![Energy dissipation slotted plate](image)

Figure 4 The Proposed energy dissipation slotted plate.

The device has ability to resist the earthquake forces that transferred from substructure to superstructure. Moreover, the device has the capability to absorb the energy by yielding of the device parts. When the earthquake forces reach to the girder the inner plate will resist and provide energy dissipation. The other plates may function along with the inner plate by the seismic forces incremental. The advantage of the proposed plate is the ability to replace the yielded parts only rather than replacing the entire damper.

4. Finite element performance of the proposed ED Plate

The multi-level performance of the proposed plate has been assessed numerically by performing nonlinear finite element analysis. Both load control and displacement control
analyses were conducted to evaluate the accuracy of the analysis for predicting the behavior of the plate. The load applied is 225KN in loading control analysis. However, 60mm displacement is applied in the displacement control analysis. The loading applied directly to the inner plate that moves toward the other plates. The boundary condition is fixed support at the other end to fix all the plates. The mesh size is same in all the ED device parts with 50*50*50mm. The material used is steel with 200GPa Young modulus and 0.3 Poisson's ratio. However, different plastic properties (S235, S400, and S460) were considered to evaluate the effect of steel grade and select the suitable grade for the developed plate. The inelastic steel properties are shown in Table 1

| Steel grade | Yielding stress (MPa) | Ultimate stress (MPa) |
|-------------|------------------------|-----------------------|
| S235        | 235                    | 360                   |
| S400        | 400                    | 510                   |
| S460        | 460                    | 540                   |

The nonlinear finite element analysis results are demonstrated in terms of stresses distributions, yielding, multi-level displacement, load-displacement curves and energy dissipation capability. Figure 5 illustrates the stresses and AC yielding of the device parts. The maximum stresses were located at middle of each plate and reduced at the edges. In addition, the yielding as same the maximum stresses appears at the middle of each plate and at the connection between slots and the non-slotted parts of the plate.

Figure 5 Stresses distribution and yielding of the proposed slotted plate (a) stresses (b) yielding.

Figure 6 depicts the multi-level displacement of the slotted plate. When load/displacement applied, the inner plate moved alone until known displacement (20mm). After that, the cubic head touched the middle (upper and lower) plate and lead to movement of both plates and reach to 40mm movement. At that time, the cubic head and the middle plates touched the outer plates and caused movement of all the plate parts. By the end of the analysis the ED plate reached to the maximum assigned displacement (60mm).
The plate multi-level performance is shown in load displacement curves that demonstrated in Figure 7 for steel with S400. For the loading control analysis, the first level showed a comprehensive resistance with very low displacement and the resistance remained almost same until finishing the first stage. In contrast, the displacement control analysis showed low resistance at the beginning of the analysis and showed gradual resistance incremental until reach to same resistance with load control by the end of the stage. When the middle plates worked, that represents the second stage, and the capacity almost duplicated in both load and displacement control analysis. The load-displacement behavior was same the first stage. The loading control showed immediate improvement in the resistance and the displacement control exhibited gradual improvement. For the last stage, same performance with pervious stages has achieved for both analysis types.
In order to predict the effect of steel grade on the plate behavior, three steel grades were used. The load displacement outputs for all grades are illustrated in Figure 8. For all steel types, the multi stages were achieved. The plate resistance will be improved in all stages by increasing the steel grade. The plate with S235 showed the lower resistance in all steps and S460 showed the higher. At the beginning of second stage, S400 plate showed better capacity than S460 but decreased by load incremental. At first and last steps, the displacement and loading incremental was smooth unlike the second step. These results indicated the importance of selecting a proper steel grade for such kind of devices.

The energy dissipation capability of the proposed plate with different steel properties is illustrated in Figure 9. The energy that dissipated by using S235 was less than 10000 KN.mm while S400 and S460 dissipated around 16000 and 17000KN.mm. This indicates that the proposed plate is able to dissipate energy comprehensively and the selecting of steel properties may effect on the overall capacity and energy absorption.
5. Seismic performance of bridge equipped with slotted plate

The ground motion effect on structural performance of bridge equipped with slotted plate is evaluated in this research.

5.1 The considered bridge and earthquake details

Bridge seismic performance without and with energy dissipation device is evaluated and Figure 10 shows the bridge and earthquake details. The bridge is two lanes four spans with 80m length and width 3.65m per lane. The bridge section was concrete box girder with 12m width and 1.7m depth. The substructure contain from three bents with one column and two abutments. The footing type was plied foundation. The bridge seismic performance is evaluated by applying El-Centro excitation on the bridge in longitudinal direction. After that, the bridge equipped with different properties of the slotted plate. The plate behavior is added to the bridge using Multi-linear plastic behavior. The load-displacement curves of plate were added after scaling up 10 times assuming that the required force of the plate is more than 2500KN to resist any earthquake.

Figure 9: Energy dissipation capacity of plate using different steel properties.

Figure 10RC: box Girder Bridge with ground motion details.
5.2 Numerical results of bridge with ED plate

The bridge deformation due to El-Centro excitation is shown in Figure 11. The bridge deformed in longitudinal direction with large displacement. The box girder has moved along with the earthquake direction. The bent showed inelastic performance while the abutments demonstrated a linear elastic performance indicating the need for adding the energy dissipation plate in the connection between girder and bent.

Figure 11 Bridge deformation due to El-Centro ground motion.

The time history analysis results are represented by time displacement for bridge without and with different properties of ED plate that depicted in Figure 12. The maximum displacement in the girder without the plate is more than 75mm at the first five seconds of applying the ground motion exhibiting the severe effect of the earthquake on the considered bridge. By adding the slotted plate, the seismic behavior of the bridge is enhanced since the displacement has decreased by equipping with S235, S400, and S460 about 68%, 90%, 91% correspondingly.

Figure 12 Time history displacement of as built bridge and bridge with the slotted plate.

6. Conclusion

This study proposed a multi-level energy dissipation slotted plate. The numerical performance of single plate, the proposed device, and the bridge performance with the plate are assessed. The study concluded that the single circular slotted pipe is not suitable to get the multi-level performance with less deformation unlike the rectangular plate. This study developed the slotted plate by using multi-layers of rectangular slotted plate. The nonlinear finite element analysis approved the plate multi-level performance. Both loading control and displacement control analysis simulated the plate performance. However, loading control analysis showed significant resistance at early stage of loading but the displacement control exhibited a gradual resistance incremental in all levels of movement. The steel grade plays important role in the plate resistance and energy dissipation capacity. The study also approved that the plate has a noteworthy effect on bridge overall performance and showed girder displacement decrease...
indicating of prevention of bridge unseating. The girder displacement has decreased by equipping with S235, S400, and S460 ED plate about 68%, 90%, 91% respectively.

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