

A new metallic bar damper device for seismic energy dissipation of civil structures

Khaled Ghaedi ¹, Zainah Ibrahim ¹ and Ahad javanmardi ¹

¹Department of Civil Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia

zainah@um.edu.my and khaledghaedi@yahoo.com

Abstract. This paper presents a new type of hysteretic metallic damper device, named bar damper (BD). BD is mainly made of three simple steel parts that includes top and bottom steel plates and a number of solid bars which dissipate input energy due to vibration loads through flexural yielding. Despite the simplicity of the damper, an optimized geometry of the plates as well as the solid bars can be suggested to guarantee uniform stress and strain distribution. Three full-scale device specimens have been made to be tested under cyclic displacement. The obtained results from the tested specimens have revealed a significant cumulative displacement extracted from the hysteresis loops with no substantial strength degradation.

1. Introduction

Structures are always prone to environmental loading such as earthquake motions which have not yet been succeeded to predict [1], which can make serious damage to engineering structures [2]–[4]. Passive control dampers have been commonly studied and utilized in different building and bridge structures as an effective system while they are relatively inexpensive devices to decrease earthquake damage [5]–[8]. Inelastic behaviour of steel materials in metallic dampers, current of viscous materials in tiny orifices inside a viscous damper and materials with viscoelastic behaviour in viscoelastic devices are some other mechanisms that have been utilized to harvest seismic energy. Kelly et al. [9] were the pioneers to study about metallic dampers and followed by Skinner et al. [10] and other researchers such as [11], [12].

Metallic dampers can effectively dissipate huge amount of seismic energy through inelastic mechanism of steel materials. The key use of these devices is to reduce structural damage induced by earthquake vibrations in prearranged or replaceable elements, subsequently prevent irrecoverable damages to primary structure. In general, depending upon the yielding behaviour, metallic dampers are classified to four categories including torsional dampers, axial dampers, flexural dampers and shear dampers. In torsional dampers, energy is dissipated mainly through torsional plastic deformation mechanism [13]. Buckling restrained brace (BRB) is a good example of axial metallic dampers which made of a case (usually concrete materials) covered a steel core to withstand against axial compression and tension forces. A frictionless coating decoupled the steel core and the concrete case to allow the system to dissipate energy efficiently [14], [15]. Added Damping and Stiffness, known as ADAS, and Triangular- ADAS, known as TADAS, dampers are the most used flexural yielding damping system [16], [17]. Seismic energy is dissipated when the ADAS and TADAS dampers are under out-of-plane bending, thus a uniform distribution of stress is generated throughout the dampers; leading harvesting energy. Moreover, ADAS and TADAS systems are made of steel plates which is usually placed in X or inverse V shape, respectively. Another sort of metallic device is yielding shear panel. Input energy will



be dissipated when the panel subjected to plastic shear deformations [18], [19]. Apart from the aforesaid metallic damper devices, other types of such dampers have been introduced when they mainly dissipate energy through torsional plastic deformation (e.g., slit damper is a type of these dampers). Slit damper is commonly recognized as a special yielding damper, where a number of opening (slit), imbedded in a plate, are exposed to an in-plane deformation [12], [20].

With regards to the previous results and interpretations of metallic dampers, the present work proposes a newly yielding damper, called bar damper, BD, consisted of a number of steel solid bars which acts in both directions and dissipates energy using flexural yielding deformation mechanism. Special attempt was done to investigate the height effect of solid bars through the experimental study to have an appropriate design of the damper, while real scale of the damper were fabricated and tested cyclically under displacement protocol.

2. Bar Damper

Figure 1(a) presents an overall view of BD attaching a beam to a column in a structural frame. The constituents of a BD can be seen in Figure 1(b). As observed, the BD harvests seismic energy through its bars taking advantage of in-plane flexural yielding. This design permits controlling axial and shear deformation of solid bars due to gravity and lateral shear force. As it can be observed from Figure 1(a), the damper primarily was designed to be installed at a beam-column connection, at the corner of a building frame. Moreover, as demonstrated in Figure 1(b), both end of the bars are welded to the upper and bottom plates to provide the rigidity, though slotted holes at the place of each bar may be provided to have a good bolt connection and sandwich the bars between the plates. It is noted that, rigidity of the bars at their ends enlarge axial elongation of the bars due to in-plane deformation. Therefore, moving back the damper to reverse position under cyclic loading creates substantial axial compressive force in the bars, resulting in damper failure under several cyclic load history. Such unwelcome occurrence reduces the different mechanical properties of the damper, i.e., energy dissipation rate, stiffness and strength of the BD device. In general, the boundary condition or the support condition of bars in BD impels them to react parallelly, once a horizontal deformation is imposed to the frame. This means that, each solid bar of the BD will be under in-plane shear force; dissipating seismic energy over flexural yielding.

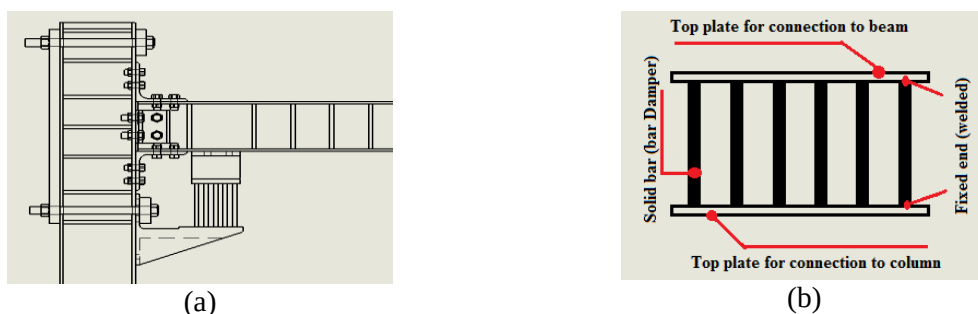


Figure 1. A typical bar damper view for (a) frame and (b) experimental test

3. Experimental Study

In order to assess the behaviour of the suggested device, three real-scale samples (BD-1, BD-2 and BD-3) were fabricated and was loaded through cyclic displacement according to FEMA 461 [21]. The plates were made from a 12 mm structural steel, whereas 10 mm diameter solid bars were provided to be sandwiched between the plates. The steel mechanical properties of the damper parts are reported in Table 1. The damper specimens considered with different heights of 100 mm, 130 mm and 160 mm where each comprising of 24 bars with 10 mm diameter. Figure 2(a) depicts the test setup of the specimens for experimental study. As observed, the damper specimen was located between a loading plate and a fixed support plate. For attaching the specimens to the plates, eight bolts were used, four each side. A brittle cover of yellow colour was applied to the surface layer of damper specimens to

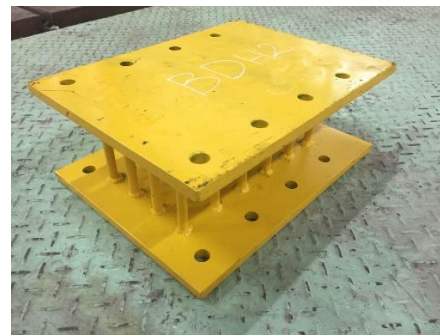
monitor the yielding form in the bars (see Figure 2(b)). Cyclic displacement load as quasi-static approach was implemented to each specimen using a 1000 kN automated- controlled universal test machine. The displacement history used for experiments was designed up to 50 mm, as presented in Figure 3.

Table 1. Properties of solid bars and plates used in fabrication of BD

Part	Diameter/Thickness (mm)	Modulus of elasticity (GPa)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (%)
Plates	12	200	340	526	24.9
Bars	10	201	341	532	23.8



(a)



(b)

Figure 2. (a) test setup of the bar damper and (b) coloured specimen

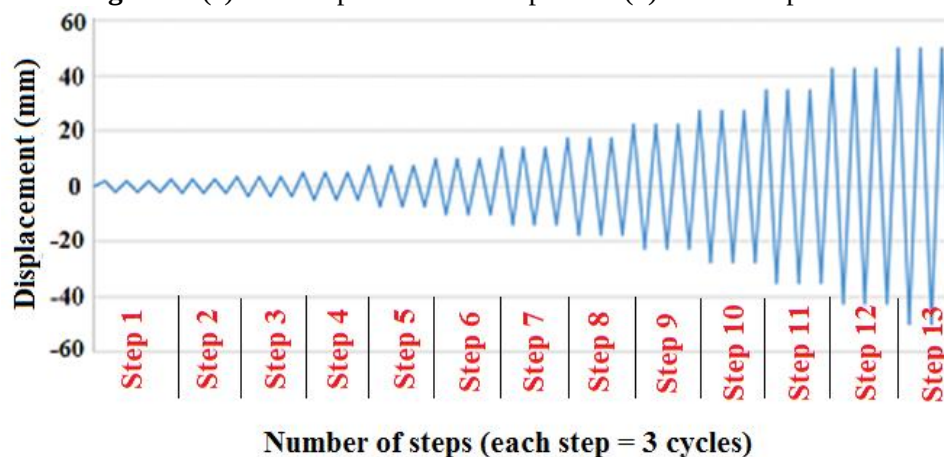


Figure 3. Displacement history of BD

4. Results and Discussions

Under the cyclic tests, deformation of all three specimens was occurred in a stable condition. The solid bars bent in double curve as estimated. Figures 4(a)–(c) demonstrate the hysteresis loop of force–displacement of BD specimens subjected to the cyclic tests. A positive indication denotes to descending force and displacement. All tested dampers yielded at relatively small movement and showed appropriate constant hysteretic performance with a gentle shift from elastic to inelastic regime. As observed from Figure 4, the response of damper specimens were smaller than the applied displacement (Figure 3). This is because of small elastic movement. The mechanical features of the damper can be determined pursuant to the total damper deformation as computed between the variance of the ends of

the bars at each side. BD-1 with 100 mm height, the shortest specimen, sustained the highest load whereas specimen BD-3 with 160 mm height, the highest specimen, sustained the lowest.

Strength degradation in specimens occurred when brittle cracking gradually formed at the ends of the solid bars as a result of stress concentration. This happened after 28, 31 and 37 cycles of loading for BD-1, BD-2 and BD-3, respectively. The precise position where these cracks started fluctuated amongst the device specimens. It can also be seen from Figure 4 that, by increasing the height of the solid bars (damper height) the load capacity of the specimens decreases, while displacement increases. It confirms that, for different seismic zones there is a simple but very effective parameter in designing BD device for structures. The test machine was shut down after a few bars completely broken at their ends at which the load capacity was considerably attenuated. It should be noted that, the eight structural bolts for connecting the specimens to each plates satisfactorily sustained under applied load; no important deformation was seen after end up the tests.

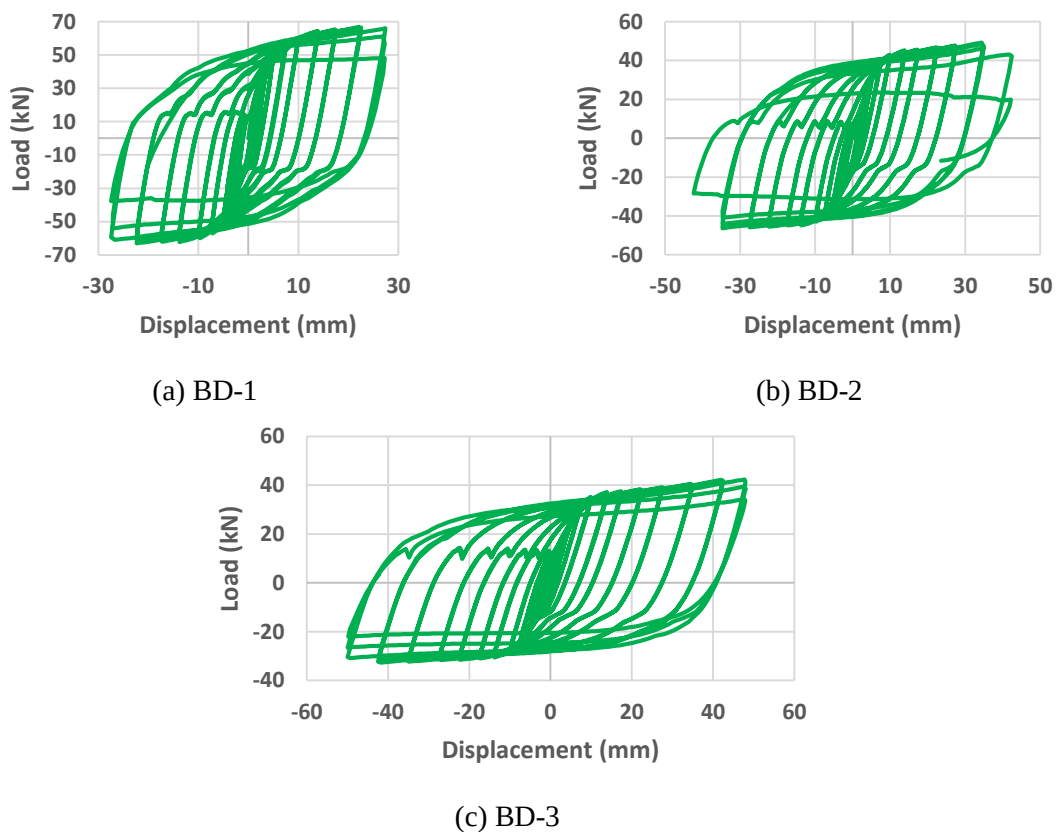


Figure 4. hysteresis behaviour of BD specimens under cyclic load

4.1 Ductility and maximum strengths

The maximum strength, P_{max} , is indicated in Table 2. Maximum positive strength values were slightly larger than the minimum strength because of the Bauschinger result. Table 2 shows that, increasing height of the damper from 100 mm to 160 mm results in decreasing strength by 43%. In contrast, travelled displacement increased by approximately 78%. Cumulatively, BD-1 with the shortest height had the shortest movement before failure. In terms of ductility which is determined by Equation (1), in which δ_{max} is the peak displacement throughout an established cycle and δ_y is the yield displacement. Herein, for simplification and better understanding of force-ductility relationship, a normalized curve, as shown in Figure 5, is presented. It is remarkable to mention that all BD devices worked in an analogous form. The tested dampers undergone ductility ratios from 24 to 55. It is obvious that, ductility ratio depends upon the imposed displacement history, hence, it varies by changing the load history.

$$\mu = \frac{\delta_{max}}{\delta_y} \quad (1)$$

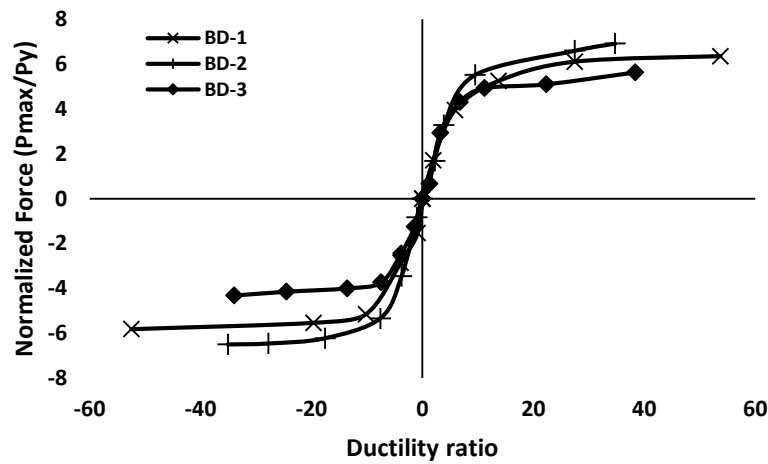


Figure 5. Envelope behaviour of BD specimens under cyclic load

Table 2. BD properties obtained from experiments

Specimen	δ_y (mm)	δ_{max} (mm)	μ	P_y (kN)	P_{max} (kN)	P_{max}/P_y	Failure cycle
BD-1	0.56	27	55	7	65	9.3	28
BD-2	0.96	34	35	5	48	9.6	31
BD-3	1.45	48	24	4	37	9.25	37

4.2 Equivalent viscous damping (EVD)

The results of hysteresis curve was utilized to assess the EVD of the BD subjected to shear force. The below recognised equation gives an acceptable approximate of the EVD.

$$\xi = \frac{E_D}{4\pi E_s} \quad (2)$$

Where, E_D represents the dissipated energy per a complete cycle under load–displacement hysteretic loop. The elastic strain energy is defined by E_s . For instance, in BD-3, from Figure 4(c) the EVD was determined as:

$$\xi = \frac{E_D}{4\pi E_s} = \frac{6138}{11256} = 54.5\%$$

A same order of EVD for BD-1 and BD-2 were obtained as 50% and 49%, respectively. These proved that, the bar damper device is able to dissipate a huge amount of input energy as fine as other existing metallic dampers in the market while BD is cost-effective and very simple.

5. Conclusion

The present paper proposed a new simple low cost metallic damper, called bar damper. The BD was fabricated from ordinarily existing structural steel materials, while no particular assembly technique is required. Therefore, the damper can effortlessly be used in practice. The BD dissipates energy using flexural yielding through the solid bars. Three cyclic displacement tests were implemented and the key conclusions are drawn below:

- BD device showed a stable behaviour under applied cyclic tests demonstrated and dissipated noteworthy volumes of energy (49%-55%) under quasi-static protocol.
- Due to simplicity of the proposed damper, the yield strength can be simply anticipated through plastic mechanism approach.
- Devices with higher height behaved more flexible. Devices with shorter height of the bars possess greater stiffness, but had earlier failure.
- The damper specimens showed their capability to dissipate a significant quantity of further energy even after solid bars failure.

Acknowledgements

The authors gratefully acknowledge financial support from the Fundamental Research Grant Scheme, Ministry of Education, Malaysia (FRGS - Project No. FP004-2014B), Postgraduate Research Grant (PPP-Project No. PG177-2016A) and PPP-Grant Project No. PG242-2015B. The BD device has been patented by MyIPO (Malaysia Intellectual Property Organizations) under patent number PI 2016702928.

References

- [1] Ghaedi, K., Z. Ibrahim, Earthquake Prediction, Earthquakes - Tectonics, Hazard and Risk Mitigation, 2017, p. 205–227.
- [2] Ghaedi, K., M. Jameel, Z. Ibrahim, P. Khanzaei, Seismic analysis of Roller Compacted Concrete (RCC) dams considering effect of sizes and shapes of galleries, KSCE Journal of Civil Engineering, Vol. 20, Issue 1, 2016, p. 261–272.
- [3] Hanif, M. U., Z. Ibrahim, M. Jameel, K. Ghaedi, M. Aslam, A new approach to estimate damage in concrete beams using non-linearity, Construction and Building Materials, Vol. 124, Issue C, 2016, p. 1081–1089.
- [4] Ghaedi, K., F. Hejazi, Z. Ibrahim, P. Khanzaei, Flexible foundation effect on seismic analysis of Roller Compacted Concrete (RCC) dams using finite element method, KSCE Journal of Civil Engineering, 2017, p. 1–13.
- [5] Javanmardi, A., Z. Ibrahim, K. Ghaedi, M. Jameel, H. Khatibi, M. Suhatri, Seismic response characteristics of a base isolated cable-stayed bridge under moderate and strong ground motions, Archives of Civil and Mechanical Engineering, Vol. 17, Issue 2, 2017, p. 419–432.
- [6] Gordan, M., H. A. Razak, Z. Ismail, K. Ghaedi, Recent developments in damage identification of structures using data mining, Latin American Journal of Solids and Structures, Vol. 14, Issue 13, 2017, p. 2373–2401.
- [7] Ghaedi, K., Z. Ibrahim, H. Adeli, A. Javanmardi, Invited Review: Recent developments in vibration control of building and bridge structures, Journal of Vibroengineering, Vol. 19, Issue 5, 2017, p. 3564–3580.
- [8] Ghaedi, K., Z. Ibrahim, M. Jameel, A. Javanmardi, H. Khatibi, Seismic Response Analysis of Fully Base-Isolated Adjacent Buildings with Segregated Foundations, Advances in Civil Engineering, Vol. 2018, 2018, p. 1–21.
- [9] Kelly, J. M., R. I. Skinner, A. J. Heine, Mechanisms of energy absorption in special devices for use in earthquake resistant structures, Bulletin of New Zealand Society for Earthquake Engineering, Issue 5, 1972, p. 63–88.
- [10] Skinner, R. I., J. M. Kelly, A. J. Heine, Hysteretic dampers for earthquake-resistant structures, Earthquake Engineering & Structural Dynamics, Vol. 3, Issue 3, 1974, p. 287–296.
- [11] Vargas, R., M. Bruneau, Effect of Supplemental Viscous Damping on the Seismic Response of Structural Systems with Metallic Dampers, Journal of Structural Engineering, Vol. 133, Issue 10, 2007, p. 1434–1444.
- [12] Oh, S.-H., Y.-J. Kim, H.-S. Ryu, Seismic performance of steel structures with slit dampers, Engineering Structures, Vol. 31, Issue 9, 2009, p. 1997–2008.
- [13] Franco, J. M., X. Cahís, L. Gracia, F. López, Experimental testing of a new anti-seismic

- dissipator energy device based on the plasticity of metals, *Engineering Structures*, Vol. 32, Issue 9, 2010, p. 2672–2682.
- [14] Tsai, K.-C. *et al.*, Pseudo-dynamic tests of a full-scale CFT/BRB frame—Part I: Specimen design, experiment and analysis, *Earthquake Engineering & Structural Dynamics*, Vol. 37, Issue 7, 2008, p. 1081–1098.
- [15] Chou, C. C., P. T. Chung, Y. T. Cheng, Experimental evaluation of large-scale dual-core self-centering braces and sandwiched buckling-restrained braces, *Engineering Structures*, Vol. 116, 2016, p. 12–25.
- [16] Bayat, M., G. R. Abdollahzade, Analysis of the steel braced frames equipped with ADAS devices under the far field records, *Latin American Journal of Solids and Structures*, Vol. 8, Issue 2, 2011, p. 163–181.
- [17] Garivani, S., A. A. Aghakouchak, S. Shahbeyk, Numerical and experimental study of comb-teeth metallic yielding dampers, *International Journal of Steel Structures*, Vol. 16, Issue 1, 2016, p. 177–196.
- [18] Formisano, A., L. Lombardi, F. M. Mazzolani, Perforated metal shear panels as bracing devices of seismic-resistant structures, *Journal of Constructional Steel Research*, Vol. 126, 2016, p. 37–49.
- [19] Chan, R. W. K., F. Albermani, S. Kitipornchai, Experimental study of perforated yielding shear panel device for passive energy dissipation, *Journal of Constructional Steel Research*, Vol. 91, 2013, p. 14–25.
- [20] Chan, R. W. K., F. Albermani, Experimental study of steel slit damper for passive energy dissipation, *Engineering Structures*, Vol. 30, Issue 4, 2008, p. 1058–1066.
- [21] FEMA, Federal Emergency Management Agency (FEMA). Interim protocols for determining seismic performance characteristics of structural and nonstructural components, Issue FEMA 461, 2007.