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Improving cyclic behavior of multi-level pipe damper using infill or slit diaphragm inside inner pipe

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Abstract. Analytical and experimental studies of the innovative pipe in pipe damper have been recently investigated by the authors. In this paper, by adding lead or zinc infill or slit diaphragm inside the inner pipe, it is tried to increase the equivalent viscous damping ratio improving the cyclic performance of the recently proposed multi-level control system. The damper consists of three main parts including the outer pipe, inner pipe and added complementary damping part. At first plastic deformations of the external pipe, then the internal pipe and particularly the added core and friction between them make the excellent multi-level damper act as an improved energy dissipation system. Several kinds of added lead or zinc infill and also different shapes of slit diaphragms are modeled inside the inner pipe and their effectiveness on hysteresis curves are investigated with nonlinear static analyses using finite element method by ABAQUS software. Results show that adding lead infill has no major effect on the damper stiffness while zinc infill and slit diaphragm increase damper stiffness sharply up to more than 10 times depending on the plate thickness and pipe diameter. Besides, metal infill increases the viscous damping ratio of dual damper ranging 6-9%. In addition, obtained hysteresis curves show that the multi-level control system as expected can reliably dissipate energy in different imposed energy levels.

Keywords: multi-level damper; metal infill; slit diaphragm; cyclic performance; ductility; numerical analysis

1. Introduction

Using steel slit dampers or metal infill is one of the methods to improve the seismic performance of the structures. Concentration of inelastic deformations in such devices to prevent damage in the other main frame members is the main idea of using this kind of metallic dampers. Besides, they are light weight, easily fabricated and easy-to-exchange after large earthquakes.

An innovative structural system with slit dampers was developed by Oh *et al*. (2009). In their proposed system, a mechanical joint equipped with a metallic damper as the beam-to-column connection was used to limit the plastic deformation in the slit dampers at the bottom flange. Cyclic tests of three full-scale steel structures demonstrated that the proposed connection had a suitable hysteretic behavior as energy dissipater. Ghabraie *et al*. (2010) and Xu *et al*. (2011) conducted research on the shape optimization of strip dampers to remove useless section at the central part of the strips. Experimental results proved that the optimized shape shows more energy dissipation capacity and is more resistant versus low-cycle fatigue.

Chana and Albermani (2008) had laboratory test on the cyclic performance of slit damper. The results show appropriate cyclic behavior of connections equipped with slit dampers. Garivani *et al*. (2014) proposed a new type of yielding metallic damper called comb-teeth damper, consisting of steel plates including a number of teeth that dissipate energy through in-plane flexural yielding. Numerical finite element modeling and test results were used to verify the proposed damper. Their results show that samples tolerated considerable displacement in their hysteresis curves without any significant loss of strength.

In another study, Seo *et al*. (2015) suggested the slit dampers made of super elastic Shape Memory Alloy (SMA) bending bars in parallel with the steel energy-dissipating damper. They analyzed several FE slit damper models subjected to cyclic loads and then calibrated the results with laboratory test. Their results proved that innovative steel slit dampers combined with super elastic SMA bending bars generate remarkable performance improvements in terms of post-yield strength and energy dissipation. In another research, Moreai and Alam (2015) studied the seismic performance of beam-column connections incorporating SMA plates that were effective in decreasing the residual drifts of a flange plate beam-column connection with a proper ductility. Also, Lee *et al*. (2015) studied the cyclic behavior of non-uniform steel strip dampers. The different strip shapes were designed to decrease stress concentration caused by cyclic loadings. Six samples were tested to evaluate the cyclic performance of the dampers. According to the results, cumulative damage was distributed throughout the strips making a typical ductile failure mode. Moreover, the experimental results showed that the

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proposed strip dampers indicate proper seismic performance compared to conventional prismatic slit dampers.

Moreover, steel pipes have been widely used as metallic damper to improve seismic behavior of Concentrically Braced Frames, CBFs. Kafi (2009) conducted numerical and experimental research on the effects of hollow steel pipes to improve seismic behavior of CBFs showing significant influence on the frame ductility and delay in brace buckling. On the other hand, although the Eccentrically Braced Frames, EBFs have ductile performance, their reconstruction and hard repair might cause inappropriate performance after earthquakes. So, Bazzaz *et al*. (2014, 2015) tried to improve the cyclic behavior of EBFs with circular dissipater to provide replacement of damaged member with no need to repair or reconstruct the general system. Their numerical results proved that the ductile performance of steel ring at the end of braces acts as a fuse to prevent buckling in the off-center bracing system. In another study, Andalib *et al*. (2014) conducted experimental research on the ductility and performance of steel rings constructed from plates regarding the effects of different types of half-ring connections. Their results showed that the braces remain in elastic zones while the steel ring is in plastic range and dissipates a large amount of energy.

Some other researchers have tried to improve the cyclic behavior of pipe by adding an infill such as lead, zinc or concrete. Maleki and Bagheri (2010) studied the hollow steel pipes filled with concrete to explore the possibility of their use as hysteresis dampers under shear stresses. Their results presented that the stiffness and strength of the pipe increased linearly with increasing the length and nonlinearly with increasing the thickness and reducing the diameter. Steel pipes filled with concrete showed no ductile behavior caused by concrete failure while hollow steel pipes have stable hysteresis behavior and high equivalent viscous damping ratios. Also, another sample of such dampers consisting of two nested pipes was proposed by Maleki and Mahjoubi (2014). The gap between the outer pipe and the inner one is filled with metals such as lead and zinc. The damper energy dissipation mechanism is based on plastic deformations of the concentric pipes, metal core and internal friction between the internal and external pipes. The results of laboratory tests on six samples showed high damping ratios and stable hysteresis behaviors. The numerical modeling was also followed to determine the optimum size of the damper and design procedure. Moreover, a lead extrusion damper is experimentally investigated by Yang *et al*. (2015). Their experimental results exhibited rectangular force-displacement hysteresis curves with force-velocity hysteresis loops showing nonlinear hysteretic characteristics. Based on the obtained results, their proposed damper can provide consistent energy dissipation without any stiffness degradation.

Using multi-level control systems is one of the new methods that attracted the attention of researchers in the recent years. The main idea of these systems is to combine different control systems with separate amounts of strength and stiffness resulting desirable energy dissipation in various earthquake intensity levels. Zahrai and Vosooq (2013) suggested a new dual system including a couple of shear links which are connected in series using chevron bracing that could correlate its performance with the amount of input energy. In their system, the inherent hysteretic damping of vertical link beam is exclusively utilized to dissipate the energy of moderate earthquakes through web plastic shear distortion. Under strong earthquakes, plastic deformation of link beam will be halted via restraining it by a stopper device such that further imposed displacement subsequently causes yielding of the knee elements located at the bottom of chevron bracing to significantly increase the energy dissipation capacity level. Based on their results, CK-VLB system shows stable behavior and is capable of dissipating a significant amount of energy in two separate energy levels. In another study combining two knee braces and a vertical link beam, Rousta and Zahrai (2017) also proposed a two-level control system to improve behavior of chevron braced steel frames. Their test results indicated appropriate performance of the proposed system in terms of ductility and energy dissipation in two different excitation levels. Cheraghi and Zahrai (2016) proposed a multi-level pipe-in-pipe damper as a new passive device, using two nested steel pipes (Fig. 1). Zahrai and Cheraghi (2017) studied seismic response of typical steel buildings equipped with Multi-level Pipe Damper (MPD) under seven earthquake excitations and showed the effectiveness of MPD to reduce the seismic response of the structures.

As shown in Fig. 1, the proposed damper consists of a combination of nested pipes that could change dynamic behavior parameters like strength, stiffness and damping ratio for energy absorption at different earthquake levels from moderate to severe conditions. The numerical and experimental results show excellent ductility and high amount of equivalent viscous damping ratio of their proposed damper. Besides, hysteresis curves demonstrate multi-level behavior with variable strength and stiffness as expected that can dissipate seismic energy in different earthquake levels.

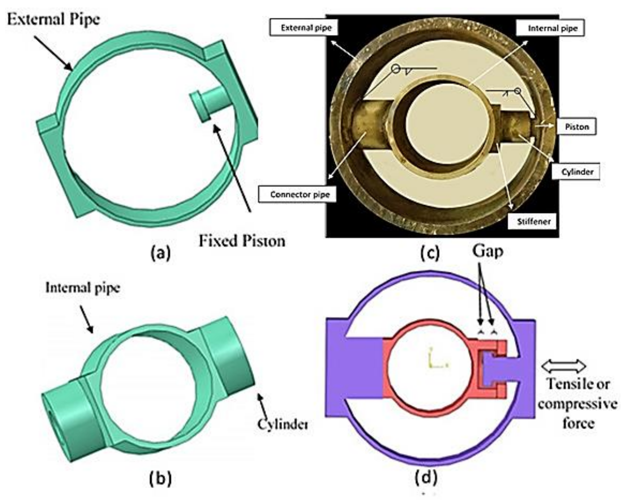

Fig. 1 (a) External pipe; (b) Internal pipe; (c) Assembled damper; (d) Cross section of the damper (Cheraghi and Zahrai 2016)

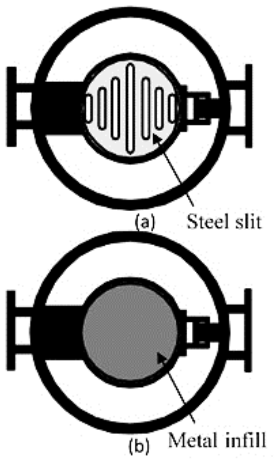

Fig. 2 Main idea of the research: (a) slit diaphragm; (b) metal infill

Table 1 Infill material properties used inside the inner pipe

Material	Modulus of elasticity [GPa]	Yield stress [MPa]	Ultimate stress [MPa]	Failure strain [%]
Lead	15	7	15	65
Zinc	100	30	60	65

Table 2 Details of single pipes with lead or zinc infill

Sample	External diameter [mm]	Thickness [mm]	Length [mm]	Core material
S 1	406	20	200	-
S 2	220	11	200	-
SC 3	406	20	200	Lead
SC 4	220	11	200	Lead
SC 5	406	20	200	Zinc
SC 6	220	11	200	Zinc

In this paper, by adding metal infill or slit diaphragm, it is tried to increase the equivalent viscous damping ratio improving the cyclic performance of damper. This main idea is presented in Fig. 2. While previous results proved the proper cyclic performance, excellent ductility and high viscous damping ratio of proposed multi-level damper, the objective of this paper is to improve its specifications with simple and inexpensive manners. Besides, it would cause to increase the damper stiffness regarding the fact that to provide the required stiffness in some structures using the bare pipe is hard or impossible and needs large pipe size increasing the costs. Moreover, absorbing some parts of input energy by metal infill or slit diaphragm increases the damper capability and performance safety factor.

2. Adding complementary damping

2.1 Ductile material as infill

Adding ductile material with high equivalent viscous damping ratio such as lead or zinc as infill inside the inner pipe of multi-level pipe-in-pipe damper is one of the methods studied in this paper. In other words, filling inside of inner pipes with lead or zinc is expected to increase energy dissipation. Using shear key such as steel angle welded inside the internal pipe seems necessary to prevent degradation in cyclic strength between inner pipe and infill material due to their different Poisson ratios. Otherwise, degradation in hysteresis curves of the damper can occur. In sample preparation process, firstly a number of shear keys with adequate length should be welded to inner surface of pipe. Then, molten infill metal fills inside the pipe. It is expected that shear keys could act as suitable connectors to achieve composite performance and transfer a major part of tensile stress.

Lead is a soft malleable and heavy metal with great density of 11340 kg/m^3. However, compared to other metals it has extremely low strength while being very ductile that tolerates large deformations before the material breaks. Also, zinc is corrosion-resistant material with density of 7140 kg/m^3 that is so tougher than lead while it has suitable ductility. Table 1 lists the infill material properties used in the damper models.

At first, to evaluate the metal infill effectiveness in cyclic performance of damper, 6 three-dimensional finite element models of a single internal pipe are modeled with the specifications listed in Table 2. According to the previous results (Cheraghi and Zahrai 2016), using the pipe with external diameter to thickness ratio about 20 ensures good cyclic behavior. So, samples specifications are selected in such a way to satisfy this criterion.

2.2 Steel slit diaphragm

Different kinds of metallic dampers can be categorized into axial, shear and flexural yielding devices or their combinations. Flexural yielding devices subjected to in-plane bending have been widely developed and applied in many structures because of their relatively higher stiffness and strength. So, adding the slit diaphragm can increase the bending capacity of multi-level pipe-in-pipe damper because of the force direction is parallel to the slit diaphragm. Besides, it seems that the slit dampers can be easily install to internal pipe by fillet or groove weld. Authors suggest using molten metal to fabricate a monolithic shape of pipe with slit plate to avoid the welding process and plate distortion because of residual stresses. Alternatively, full penetration weld can be used to provide adequate ductility. Experimental verification for these two scenarios is recommended before using them in engineering practice.

Various shapes of slit diaphragms are modeled and compared to each other to find the suitable shape to increase the equivalent damping ratio and ductility of damper. The various shapes of slit diaphragms are presented in Fig. 3. It should be mentioned that all slit diaphragms have the same cross sectional area to concentrate the shape effect only on stiffness and eliminate the other parameters such as amount of material damping.

Like previous section, in this part to evaluate the slit diaphragm effectiveness on cyclic performance of damper, 5 three-dimensional finite element models of a single internal pipe with external diameter, thickness and length of

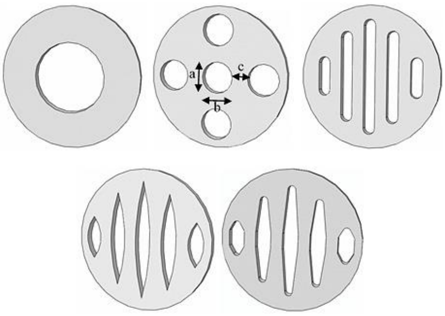

Fig. 3 Various shapes of slit diaphragms used inside the inner pipe

Table 3 Details of single pipes with slit diaphragm

Sample	Slit shape	*a* [mm]	*b* [mm]	*c* [mm]	Slit diameter [mm]	Slit thickness [mm]
SS1	Simple circle	180	180	-	366	20
SS2	Several circles	80	80	-	366	20
SS3	groove	260	30	30	366	20
SS4	arcuate	300	40	30	366	20
SS5	rhombic	280	40	30	366	20

406, 20 and 200mm respectively are modeled with the specifications listed in Table 3 and their performance under cyclic loading is observed where a is the maximum height or diameter of the holes, *b* is the width or diameter of holes, *c* is the gap between holes.

3. Finite element method

In this section, using the ABAQUS (2010) finite element software and nonlinear static analysis on a 3-D model, damper behavior is evaluated. 3D-stress 8 node nonlinear solid element type is used while material and geometric nonlinearities are activated and analysis is performed with respect to the effects of large deformations. The interactions between pipes and pipes with metal infill consisting of normal and tangential components are considered with penalty friction of hard contact. Friction coefficient between lead and steel is considered 0.95 while amount of 0.55 is used to model friction between zinc and steel in the samples that is similar to friction coefficient used in Maleki and Mahjoubi (2014) tests.

The surface to surface contact method is used to permit separation between pipes and metal infill to simulate real performance. The cyclic loading history, as shown in Fig. 4 is selected according to the ATC-24 (1992) that means 3 cycles are applied to the specimens at 0.125, 0.5, 1, 2, 3 times of yield displacement and then 2 cycles until maximum displacement.

Besides, to verify the numerical modeling and results, a sample is modeled according to the cyclic test by Cheraghi and Zahrai (2017) and results are compared with each other. As observed in Fig. 5 the hysteresis curves show suitable agreement between the numerical and experimental results. The deformed shape of a specimen at the end of the cyclic test is shown in Fig. 6.

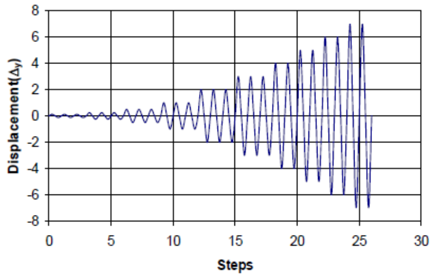

Fig. 4 Loading protocol according to ATC-24 (1992)

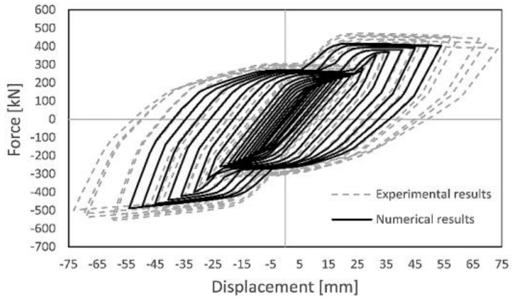

Fig. 5 Numerical hysteresis diagrams (solid) compared to experimental results (dotted)

Fig. 6 Details of failure of the test sample (Cheraghi and Zahrai 2017)

4. Materials used in the analysis

The material properties of pipes are considered based on the result of coupon test elsewhere (Cheraghi and Zahrai 2017). The tensile test results are presented in Table 4. Besides, st37 steel material is used for slit diaphragms. So, the yield stress, modulus of elasticity and Poisson's ratio are considered equal to 240 MPa, 200 GPa and 0.3, respectively.

5. Analysis results

5.1 Results of the adding metal infill

Hysteresis curves of samples SC3 and SC4 (lead infill), also SC5 and SC6 (zinc infill) show suitable symmetrical

Table 4 Material properties of pipe

Material	Yield stress [MPa]	Ultimate stress [MPa]	Failure strain [%]
Steel	295	561	25.2

Table 5 Results of single pipe samples with metal infill

Sample	K_e [kN/mm]	K_e/Ke_P	Δy [mm]	P_y [kN]	$P_{\max}$ [kN]
S 1	27.72	1	5.46	151.35	252.65
S 2	28.15	1	3.12	87.83	173.12
SC 3	34.91	1.26	5.46	190.61	330
SC 4	35.84	1.27	3.12	111.82	246.14
SC 5	58.46	2.1	5.46	319.19	548.35
SC 6	60.12	2.14	3.12	187.57	456.98

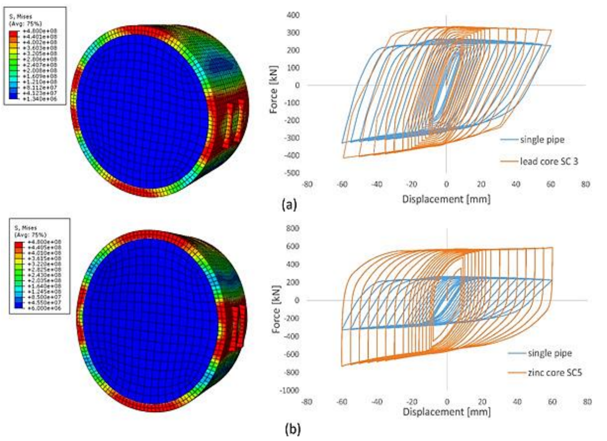

Fig. 7 Hysteresis diagrams and stress distribution of single pipe samples with metal infill: (a) SC3 sample, (b) SC 5 sample

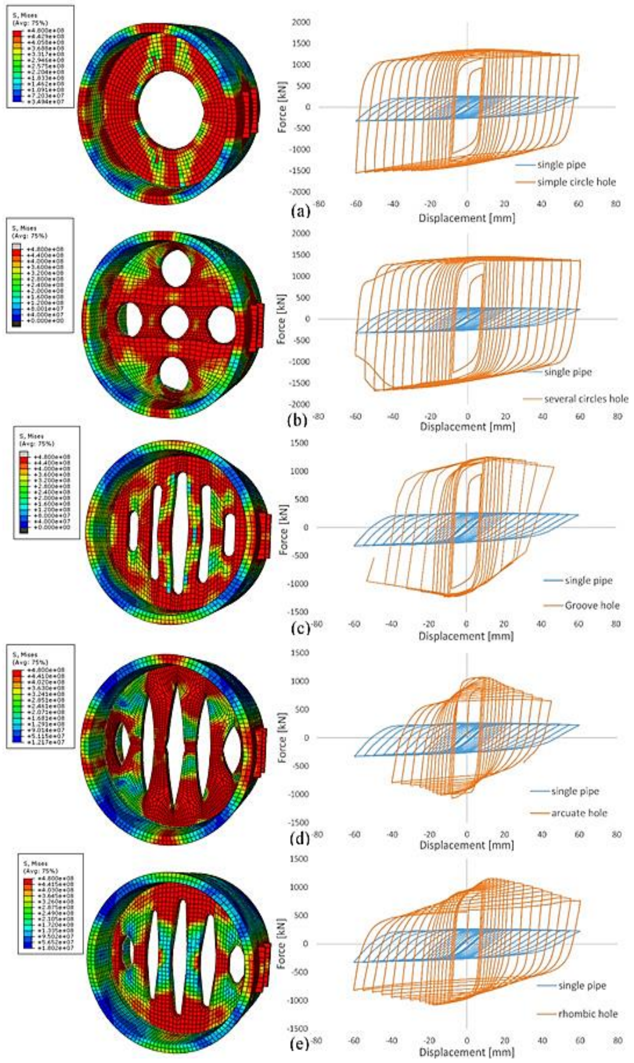

Fig. 8 Hysteretic curves and stress distribution of single pipe samples with slit diaphragm: (a) SS 1, (b) SS 2, (c) SS 3, (d) SS 4, (e) SS 5

behavior without any sign of strength or stiffness degradation. High energy absorption and stability curves in all four samples show good performance under cyclic loading. For example, hysteresis curves of samples SC3 and SC5 are presented in Figs. 7(a) and 7(b) respectively. As observed, one important note is that zinc infill results in higher stiffness and strength due to its material specifications. So, it is more effective in case of the extra lateral displacement problem in structures.

Also stress distribution in the samples indicates the plastification of metal infill increases the equivalent viscous damping ratio dissipating the vibration more quickly. The results tabulated in Table 5 where K_e is the elastic stiffness of each samples and K_{ep} is the elastic stiffness of bare pipe.

5.2 Results of adding steel slit diaphragm

Hysteresis curves of samples SS1 to SS5 are presented in Figs. 8(a) to 8(e). As observed, all shapes of slit diaphragms result in sharp stiffness and strength increase in hysteresis curves that is so useful to decrease the lateral displacement of structures. Among the different shapes, sample SS1 and SS2 that mean simple circular hole and several circular holes show the proper and symmetrical behavior without any sign of strength and stiffness degradation (Figs. 8(a) and 8(b)). Besides, High energy absorption and stability curves in this shape of slit diaphragm show good performance under cyclic loading. Stress distribution in these samples indicates a full plastification of slit diaphragms while pipe is in linear range in many cases decreasing the failure possibility.

Also, as shown in Fig. 8(c) to 8(e), other slit diaphragm shapes have non-ductile behavior in which sharp stiffness and strength degradations are observable. It could be interpreted that it is because of the groove direction, i.e., perpendicular to the force direction. In other words, the longitudinal holes throughout the plate cause sharp stiffness reduction and sample damage due to the repeating expansion and contraction of grooves under cycling loading especially in sharp corners. The results are tabulated in Table 6 where K_{ep} is the elastic stiffness of bare pipe.

5.3 Results for the multi-level pipe-in-pipe damper

In this section, the effectiveness of metal infill and slit diaphragm on cyclic performance of multi-level dampers is

Table 6 Results of single pipe samples with slit diaphragms

sample	K_e [kN/mm]	K_e/K_{ep}	Δ_y [mm]	P_y [kN]	$P_{\max}$ [kN]
SS1	562.75	20.3	1.31	737.2	1348.11
SS2	610.58	22.03	1.3	793.75	1461.89
SS3	574.1	20.71	1.29	740.59	1254.16
SS4	530.64	19.14	1.3	689.83	1065.7
SS5	544.63	19.65	1.3	708.02	1155.4

Table 7 Specifications of multi-level pipe-in-pipe damper samples with metal infill

Sample	D_e [mm]	D_i [mm]	t_e [mm]	t_i [mm]	Infill material
D.S.L.I 1	610	406	30	20	lead
D.S.L.I 2	610	220	30	11	lead
D.S.Z.I 3	610	406	30	20	zinc
D.S.Z.I 4	610	220	30	11	zinc

studied. Lead or zinc infill (D.S.L.I or D.S.Z.I) are installed on 4 specimens to investigate their impacts on increasing the equivalent viscous damping ratio. Besides, according to the previous results, the simple circular shape hole slit diaphragm that showed best symmetric hysteresis curve is added to the 8 dual samples (D.S.S.D). The specifications of samples with metal infill or slit diaphragm are tabulated in Tables 7 and 8 respectively. D_e and D_i respectively are the diameter of the external and internal pipes, while t_e and t_i are their thickness. Also, D_s, D_h and t_s are the slit diaphragm diameter, hole diameter and slit diaphragm thickness respectively.

Hysteretic curves of dual samples with metal infill show suitable cyclic behavior without significant strength and stiffness degradation in all samples (Fig. 9). Moreover, the

Table 8 Specifications of multi-level pipe-in-pipe damper samples with slit diaphragms

Sample	D_e [mm]	D_i [mm]	t_e [mm]	t_i [mm]	t_s [mm]	D_s [mm]	D_h [mm]
D.S.S.D 1	610	406	30	20	20	366	180
D.S.S.D 2	610	324	30	15	15	294	74
D.S.S.D 3	610	220	30	11	11	198	50
D.S.S.D 4	508	324	25	15	15	294	74
D.S.S.D 5	508	220	25	11	11	198	50
D.S.S.D 6	508	168	25	8	8	152	38
D.S.S.D 7	406	220	20	11	11	198	50
D.S.S.D 8	406	168	20	8	8	152	38

hysteretic curves show the expected multi-level behavior such that energy dissipation in different force levels has been provided. As shown in Figs. 9(a) and 9(b), the lead infill has less effect on increasing the damper stiffness while as observed in Figs. 9(c) and 9(d), zinc infill has main effect on damper stiffness based on the higher modulus of elasticity that should be noted in design procedures.

Cyclic behaviors for all specimens are shown in Fig. 10. Comparison between the samples with and without slit diaphragm proves the sharp stiffness differences as a result of adding diaphragm inside the inner pipe. Stiffening the inner pipe increases its bending capacity and overall bending capacity of damper. Calculating the slit diaphragm thickness, number of plates and hole size are based on the required bending capacity to limit the lateral displacement of structure. Hysteretic curves for D.S.S.D.1 show proper symmetric behavior without strength and stiffness degradation until a displacement up to 75 mm. The outer pipe, inner pipe and slit diaphragm resist about 21, 20 and 59% respectively of the 1294 kN total force. Von Mises

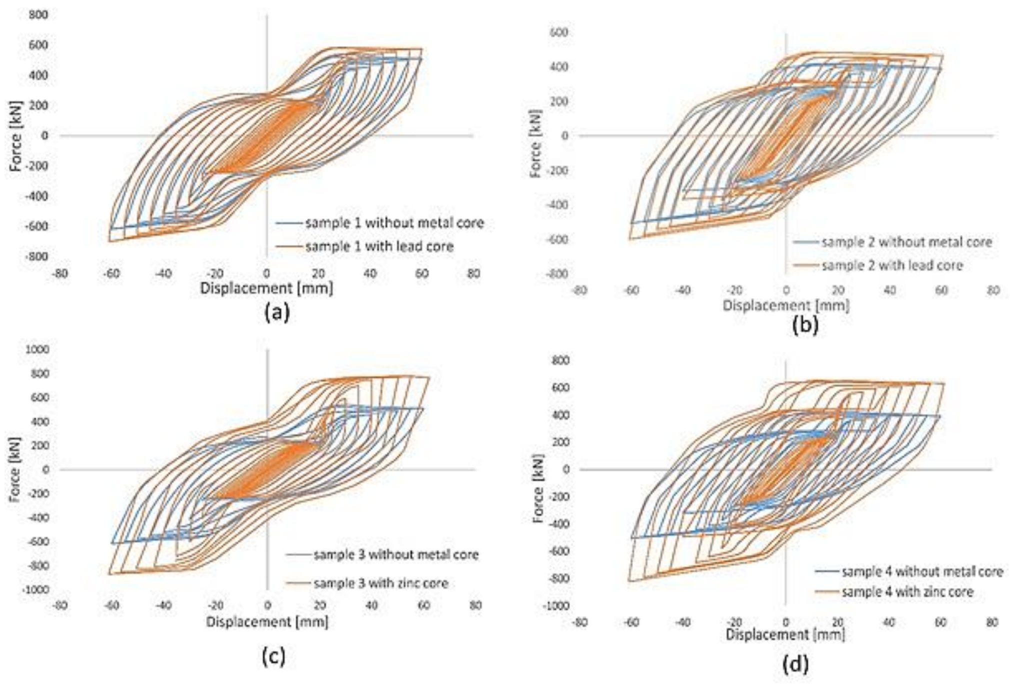

Fig. 9 Hysteretic curves of multi-level samples with metal infill: (a) D.S.L.I 1, (b) D.S.L.I 2, (c) D.S.L.I 3, (d) D.S.L.I 4

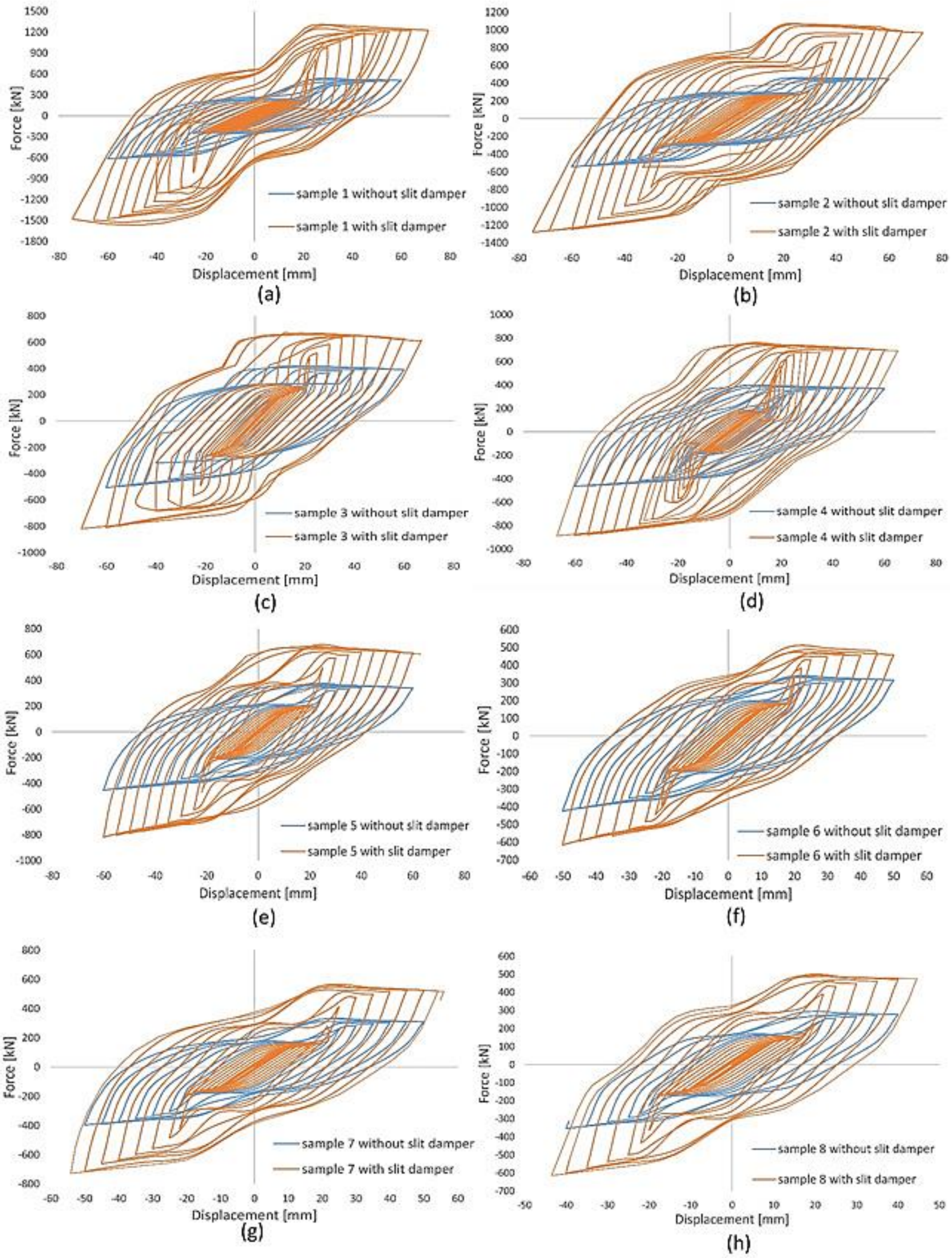

Fig. 10 Hysteretic curves of multi-level samples with slit diaphragm: (a) D.S.S.D 1, (b) D.S.S.D 2, (c) D.S.S.D 3, (d) D.S.S.D 4, (e) D.S.S.D 5, (f) D.S.S.D 6, (g) D.S.S.D 7, (h) D.S.S.D 8

stress distribution is shown in Fig. 11. As shown in Fig. 11(b) due to the higher stiffness, the maximum stresses of inner part are concentrated on the slit diaphragm and reduced stresses in the internal pipe. Besides, the results of all metal infill and slit diaphragm samples are presented in Tables 9 and 10. F_{pe}, F_{pi}, $Fs.d$ and $F_{m.c}$ respectively are the force amount tolerated by external pipe, internal pipe, slit diaphragm and metal infill.

Results show that the major part of input energy is absorbed by slit diaphragm. As it can be observed, about 39-60% of total force is in slit diaphragm due to its high axial capacity. So, it results in suitable safety factor to prevent failure in external and internal pipe of the dual damper. In case of damage or failure in slit diaphragm, it is expected that inner and outer pipes continue their composite performance. Moreover, despite its less stiffness, metal infill tolerated 16-31% of input energy.

6. Ductility assessment

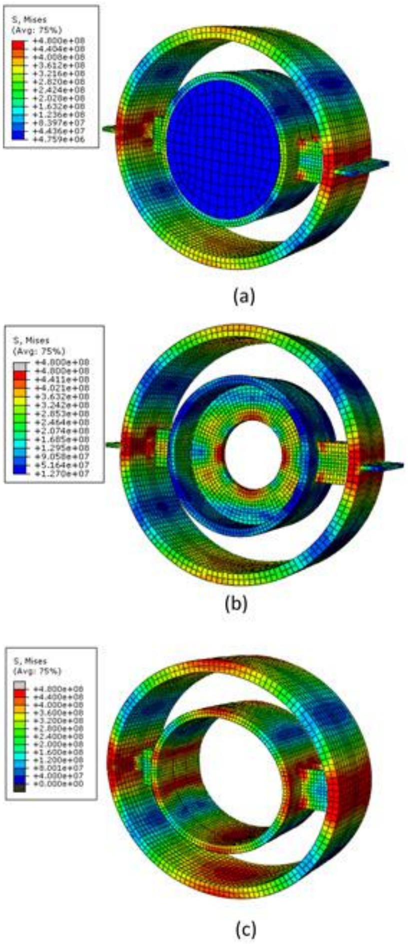

Fig. 11 Stress distribution in multi-level samples: (a) D.S.L.I 1, (b) D.S.S.D 1, (c) D.S.1

Table 9 Force distribution in different parts of dual dampers with metal infill

Sample	F_{tot} [kN]	F_{pe} [kN]	F_{pi} [kN]	$F_{m.c}$ [kN]	F_{pe}/F_{tot} [%]	F_{pi}/F_{tot} [%]	$F_{m.c}/F_{tot}$ [%]
D.S.L.C 1	637.29	269.53	252.84	114.92	20.83	19.54	18.03
D.S.L.C 2	498.12	286.94	132.12	79.06	42.88	19.74	15.87
D.S.Z.C 3	755.47	269.53	252.84	233.1	20.83	19.54	30.85
D.S.Z.C 4	565.76	286.94	132.12	146.7	42.88	19.74	25.93

Table 10 Force distribution in different parts of dual dampers with slit diaphragm

Sample	F_{tot} [kN]	F_{pe} [kN]	F_{pi} [kN]	$F_{s.d}$ [kN]	F_{pe}/F_{tot} [%]	F_{pi}/F_{tot} [%]	$F_{s.d}/F_{tot}$ [%]
D.S.S.D 1	1293.69	269.53	252.84	771.32	20.83	19.54	59.62
D.S.S.D 2	1030.93	297.92	164.25	568.76	28.90	15.93	55.17
D.S.S.D 3	669.24	286.94	132.12	250.18	42.88	19.74	37.38
D.S.S.D 4	742.25	223.16	167.5	351.59	30.07	22.57	47.37
D.S.S.D 5	650.37	223.78	143.35	283.24	34.41	22.04	43.55
D.S.S.D 6	530.11	223.43	110.63	196.05	42.15	20.87	36.98
D.S.S.D 7	555.32	183.36	143.3	228.66	33.02	25.80	41.18
D.S.S.D 8	467.36	180.49	106.2	180.67	38.62	22.72	38.66

Ductility amounts in different metal infill and slit diaphragm samples are evaluated to investigate the proposed damper effect on the structural ductility improvement. This ratio is equal to the maximum displacement to yield displacement and can be calculated using the Eq. (1)

$$\mu = \frac{\Delta max}{\Delta y} \tag{1}$$

Table 11 Ductility ratios for the dual dampers with metal infill

sample	K_1 [kN/mm]	K_{2ip} [kN/mm]	K_{2wm} [kN/mm]	K_{2wm}/K_{2ip} [kN/mm]	Δ_y [mm]	P_y [kN]	Δ_u [mm]	μ
D.S.L.C 1	18.53	25.95	32.13	1.24	8.9	164.9	208.1	23.38
D.S.L.C 2	18.53	18.76	22.66	1.21	8.9	164.9	157.9	17.74
D.S.Z.C 3	18.53	25.95	83.8	3.23	8.9	164.9	209.3	23.52
D.S.Z.C 4	18.53	18.76	58.14	3.1	8.9	164.9	160.7	18.06

Table 12 Ductility ratios for the dual dampers with slit diaphragm

sample	K_1 [kN/mm]	K_{2ip} [kN/mm]	K_{2ws} [kN/mm]	K_{2ws}/K_{2ip} [kN/mm]	Δ_y [mm]	P_y [kN]	Δ_u [mm]	μ
D.S.S.D 1	18.53	25.95	176.17	6.79	8.9	164.9	215.6	24.22
D.S.S.D 2	18.53	19.52	196.87	10.09	8.9	164.9	202.3	22.73
D.S.S.D 3	18.53	18.76	173.63	9.26	8.9	164.9	164.3	18.46
D.S.S.D 4	19.54	19.56	153.4	7.84	6.7	130.95	260.1	38.82
D.S.S.D 5	19.54	20.92	118.46	5.66	6.7	130.95	158.6	23.67
D.S.S.D 6	19.54	19.36	103.66	5.35	6.7	130.95	112.3	16.76
D.S.S.D 7	19.4	23.38	135.46	5.79	5.46	105.97	209.2	38.32
D.S.S.D 8	19.4	19.36	89.6	4.63	5.46	105.97	73.8	13.52

Sample dampers parameters are compared in the Tables 11 and 12. As can be found, lead infill has mild effect on increasing the secondary stiffness up to 21-24% while damper stiffness increases about 3.1-3.23 times in case of using zinc infill. Besides, slit diaphragm results sharp stiffness enhancement due to its high axial stiffness ranging 4.63-10.09 times of the bare pipe stiffness. Moreover, while the dual damper without metal infill and slit diaphragm showed suitable ductility ratio amount, both new ideas studied here result in achieving higher ductility ratios.

K_1 is the initial stiffness related to outer part, K_{2ip} is the secondary stiffness related to the elastic stiffness of internal pipe plus post-yield stiffness of outer pipe after having contacts between two parts and K_{2ws} is the same with K_{2ip} plus elastic stiffness of slit diaphragm. Also K_{2wm} is the same with K_{2ip} plus elastic stiffness of metal infill. So, the secondary stiffness is mixed stiffness related to the diameter to thickness ratio of inner pipe, pipe length (L) and the plastic stiffness of outer pipe, thickness of slit plate, diameter to thickness ratio of slit diaphragm and hole diameter.

7. Equivalent viscous damping ratio

Equivalent viscous damping ratios for all samples are calculated according to the Eq. (2) regarding to the hysteretic curves under cyclic loading

$$\xi_{eq} = \frac{A_h}{4\pi A_e} \tag{2}$$

Table 13 Equivalent viscous damping ratios of the proposed samples

sample	A_h @ 10 Δ_y [J]	A_e [J]	ζ [%]
D.S.L.C 1	182301	26700.54	54.36
D.S.L.C 2	142487	21360.45	53.11
D.S.Z.C 3	247228	35600.89	55.29
D.S.Z.C 4	189243	28925.1	52.09
D.S.S.D 1	315250	49060.8	51.16
D.S.S.D 2	255613	42754.88	47.6
D.S.S.D 3	171655	27273.56	50.11
D.S.S.D 4	132602	22743.44	46.42
D.S.S.D 5	110563	19956.39	44.11
D.S.S.D 6	81015	14879.48	43.35
D.S.S.D 7	71284	14892.34	38.11
D.S.S.D 8	58458	12997.12	35.81

A_h and A_e are respectively indicative of the energy dissipation in a cycle of loading and the amount of energy stored in a linear elastic system.

Considering the results of the cyclic loading and hysteretic curves, the equivalent viscous damping ratio is presented in Table 13. For comparison, equivalent damping ratios at 10 times of the yield displacement are calculated for all samples.

Results demonstrate that lead and zinc infill leads to 6-9% enhancement in equivalent viscous damping ratio of samples, while slit diaphragm does not show major effect on damping ratio. It seems concentrating the stress on the plate due to the high stiffness caused sharp strength enhancement and less effect on damping increment. So, using thinner diaphragm plate with less stiffness can be suggested in case of the problem is only less damping ratio not excessive lateral displacement. As summary, achieving 36-55% of damping ratio without use of complex energy dissipation devices confirms the effective operation of the proposed ideas for the multi-level pipe-in-pipe damper.

8. Conclusions

In this paper, by adding metal infill or slit diaphragm to the recently proposed multi-level pipe-in-pipe damper, it was tried to increase the equivalent viscous damping ratio improving the cyclic performance of damper. Results of this research can be summarized as follows:

1- Hysteresis curves represented the symmetric multi-level behavior with variable strength and stiffness that could dissipate input energy in various earthquake levels.

2- Although the bare dual damper without metal infill and slit diaphragm showed suitable ductility ratio ranging 11-36, both of new complementary damping ideas led to achieving higher ductility ratios up to about 13-38.

3- Around 39-60% of input energy was absorbed by slit diaphragm due to its high axial capacity. So, it resulted in suitable safety factor to prevent failure in external and internal pipe of the dual damper.

4- Adding the lead infill had mild effect on increasing the secondary stiffness up to 21-24% while damper stiffness increased about 3.1-3.23 times in case of using zinc infill. Besides, slit diaphragm resulted in sharp stiffness enhancement due to its high axial stiffness ranging 4.63-10.09 times of the bare pipe stiffness that could decrease the lateral displacement of structure. So, each idea discussed in this paper can be selected based on the retrofitting philosophy.

5- Among the different shapes of slit diaphragms, the one with simple circular hole and several circular holes showed a proper and symmetrical behavior without any sign of strength and stiffness degradation.

6- Results demonstrated that lead or zinc infill causes 6-9% enhancement in equivalent viscous damping ratio of samples. Overall, equivalent viscous damping ratios about 36-55% were achieved.

References

ABAQUS Finite Element Analysis Program (2010), Version 6.10.0. User's Manual.

Andalib, Z., Kafi, M.A., Kheyroddin, A. and Bazzaz, M. (2014), "Experimental investigation of the ductility and performance of steel rings constructed from plates", *J. Constr. Steel Res.*, **103**, 77-88.

Applied Technology Council (1992), "Guidelines for seismic testing of components of steel structures", Report of ATC-24.

Bazzaz, M., Andalib, Z., Kafi, M.A. and Kheyroddin, A. (2015). "Evaluating the performance of OBS-C-O in steel frames under monotonic load", *Earthq. Struct.*, **8**, 699-712.

Bazzaz, M., Kheyroddin, A., Kafi, M.A., Andalib, Z. and Esmaeili, H. (2014). "Seismic performance of off-centre braced frame with circular element in optimum place", *Steel Compos. Struct.*, **14,** 293-304.

Chana, R.W.K. and Albermani, F. (2008), "Experimental study of steel slit damper for passive energy dissipation", *J. Eng. Struct.*, **30**, 1058-1066.

Cheraghi, A and Zahrai, S.M. (2016), "Innovative multi-level control system with concentric pipes to reduce seismic response of braced steel frames", *J. Constr. Steel Res.*, **127**, 120-137.

Cheraghi, A. and Zahrai, S.M. (2017), "Cyclic testing of innovative multi-level pipe in pipe damper", *J. Earthq. Eng.* (in press)

Garivani, S., Aghakouchak, A.A. and Shahbeyk, S.H. (2014), "An efficient energy dissipating device called comb teeth damper", *Proceedings of the 2nd European Conference on Earthquake Engineering and Seismology*, Istanbul-Turkey.

Ghabraie, K., Chan, R., Huang, X. and Xie, Y.M. (2010), "Shape optimization of metallic yielding devices for passive mitigation of seismic energy", *Eng. Struct.*, **32**, 2258-2267.

Kafi, M.A. (2009), "Experimental research of the effect of steel pipes on concentrically braced frame", Ph.D. Thesis. University of Science and Technology, Department of Civil Engineering, Iran, Tehran. (in Persian)

Lee, H.C., Ju, K.Y., Min, K.J., Lho, H.S. and Kim, D.S. (2015), "Non-uniform steel strip dampers subjected to cyclic loadings", *J. Eng. Struct.*, **99**, 192-204.

Maleki, S.H. and Bagheri, S. (2010), "Pipe damper, Part I: Experimental and analytical study", *J. Constr. Steel Res.*, **66**, 1088-1095.

Maleki, S.H. and Mahjoubi, S. (2014), "Infilled-pipe damper", *J. Constr. Steel Res.*, **98**, 45-58.

Moradi, S. and Alam, M.S. (2015), "Feasibility study of utilizing super elastic shape memory alloy plates in steel beam-column connections for improved seismic performance", *J. Intell. Mater. Syst. Struct.*, **26**, 463-475.

Oh, H.S., Kim, J.Y. and Ryu, S.H. (2009), "Seismic performance of steel structures with slit dampers", *J. Eng. Struct.*, **31**, 1997-2008.

Rousta, A.M. and Zahrai, S.M. (2017), "Cyclic testing of innovative two-level control system: Knee brace & vertical link in series in chevron braced steel frames", *Struct. Eng. Mech.* **64**(3). (in Press)

Seo, J., Kim, C.Y. and Hu, W.J. (2015), "Pilot study for investigating the cyclic behavior of slit damper systems with recentering Shape Memory Alloy (SMA) bending bars used for seismic restrainers", *J. Appl. Sci.*, **5**, 187-208.

Xu, Y., Li, A., Zhou, X. and Sun, P. (2011), "Shape optimization study of mild steel slit dampers", *Adv. Mater. Res.*, **168**, 2434-2448.

Yang, M.F., Xu, Z.D. and Zhang, X.C. (2015), "Experimental study on lead extrusion damper and its earthquake mitigation effects for large-span reticulated shell", *Steel Compos Struct.*, **18,** 481-496.

Zahrai, S.M. and Cheraghi, A. (2017), "Reducing seismic vibrations of typical steel frames using new multi-level pipe damper", *Int. J. Steel Struct.*, **17**, 983-998.

Zahrai, S.M. and Vosooq, A.K. (2013), "Study of an innovative two-stage control system: Chevron knee bracing & shear panel in series connection", *Struct. Eng. Mech.*, **47**, 881-898.

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