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Experimental investigation on hysteretic behavior of rotational friction dampers with new friction materials

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Abstract. Friction dampers are displacement dependent energy dissipation devices which dissipate earthquake energy through friction mechanism and widely used in improving the seismic behavior of new structures and rehabilitation of existing structures. In this paper, the cyclic behavior of a friction damper with different friction materials is investigated through experimental tests under cyclic loading. The damper is made of steel plates, friction pads, preloaded bolts and hard washers. The paper aims at investigating the hysteretic behavior of three friction materials under cyclic loading to be utilized in friction damper. The tested friction materials are: powder lining, super lining and metal lining. The experimental results are studied according to FEMA-356 acceptance criteria and the most appropriate friction material is selected by comparing all friction materials results.

Keywords: passive energy dissipation system; friction damper; cyclic loading; hysteretic curve; brake lining

1. Introduction

Earthquake ground motions induce large amounts of energy into structures. In seismic design methods, it is assumed that part of earthquake energy is dissipated by specially designed structural elements through plastic deformation and hysteretic behavior (Aiken and Kelly 1993). During last decades, energy dissipation systems have been used in seismic design of new structure and retrofitting of existing structure and several energy dissipation systems have been developed (Constantinou *et al* 2001). Passive control systems such as base isolation or dampers are one of the most practical methods to increase the energy dissipation capacity of structures and to reduce seismic damage due to earthquake excitement (Symans and Constantinou 1999). Several mechanisms have been used by researchers to develop passive energy dissipation devices.These mechanisms include yielding of metals, phase transformation of metals, friction, deformation of viscoelastic materials and fluid orificing (Kelly *et al*. 1972). Dry friction is the basic mechanism of many dampers in which the energy is dissipated by means of the slippage between two surfaces in contact, which are clamped by means of the application of hydraulic pressures, electromagnetic forces or by means of high strength bolts. Friction dampers are displacement-dependent dampers because their sliding forces do not depend on the velocity and frequency content of excitation. The cyclic behaviors of friction dampers depend on the value of the load normal to the surfaces in contact and on the friction coefficient, which is an intrinsic characteristic of the sliding interface. The friction coefficient depends on several phenomena, such as adhesion, ploughing and the presence of contaminants. Many efforts have been made to characterize the hysteretic behavior of sliding metallic surfaces with different superficial treatments clamped by means of high strength friction grip bolts (Latour *et al*. 2014). Pall and Marsh (1981) introduced friction dampers at the intersection of braces, which adopted asbestos brake lining pads between steel sliding surfaces. Fitzgerald *et al*. (1989) employed Slotted Bolted Connection (SBC) in bracing as a friction damper in which the axial forces in the brace activated the friction. Sumitomo proposed a friction damper which utilized spring and friction pads (Aiken and Kelly 1990). Fluor Daniel Inc. performed experimental analysis on a friction damper which designed similar to Sumitomo friction damper and uses steel and bronze friction pads (Nims *et al*. 1993). Tremblay and Stiemer (1993) proposed a friction damper which used bolted slotted plates located at the end of a conventional bracing member. The brace-to-frame connection was designed to slip before yielding or buckling of the brace. In this device, friction is developed through the sliding of steel surfaces and disc spring washers were used in order to maintain the slip load. Li and Reinhorn (1995) investigated the seismic behavior of a reinforced concrete building with friction dampers through experimental and analytical study. Dorka *et al*. (1998) studied the effect of friction damper device in MDOF systems. Mualla and Beleve (2002) proposed a friction

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damper consisted of three steel plates and prestressed bolts to hold the plates together and two friction pad discs were inserted between the steel plates. Wu *et al*. (2005) improved pall frictional damper with some advantages such as ease of manufacture and assembly. Castaldo and Tubaldi (2015) investigated the seismic response of buildings with friction pendulum isolator system using the results of a series of parametric study on isolator and building properties.

Moreover, many researches have been performed to develop design procedures for friction dampers. For example; Cherry and Filiatrault (1990) proposed a design approach to optimize the slip force in friction damped braced frame structures. Colajanni and Papia (1995) investigated the seismic response of braced frames with and without friction dampers through analytical study. Bhaskararao and Jangid (2006) suggested numerical models for seismic analysis of structure connected with friction dampers. Xu and Ng (2006) performed analytical studies on seismic response control of structure using friction damper. Park *et al*. (2007) proposed procedures to linearize a friction damper–brace system based on the probability distribution of the extreme displacement. Lee *et al*. (2008) proposed a methodology to estimate slip force of friction dampers for seismically excited building structure based on story shear force distribution. Min *et al*. (2010) proposed a simple procedure to design a friction damper for reducing seismic responses of a single story structure. Vaseghi *et al*. (2011) studied seismic performance of eccentric brace steel frames systems with friction damper through finite element analysis and concluded that friction damper decreases the seismic response of structure compared to EBF particularly in tall buildings. Montuori *et al*. (2013) suggested an approach for the seismic design of a MR-frame and Bracing system with friction dampers. Saeed Monir and Zeynali (2013) introduced a modified friction damper which provides additional stiffness. Maleki and Mahjoubi (2013) introduced and studied the dual-pipe damper as a new passive earthquake energy dissipative device through experimental and analytical approach.

Papadopoulos *et al*. (2013) tested a friction device which consists of a set of rotational friction flanges and a link element for strengthening RC and steel buildings. Cheng and Chen (2014) conducted 32 shake table tests to study seismic performance of rocking bridge pier substructures with friction dampers and compared the results with analytical models. Zahrai *et al*. (2015) used friction dampers for retrofitting a steel structure with masonry infill panels and concluded that the combination of infill panels and friction dampers reduces seismic response of structure. In continues effort for using friction mechanism in dissipation energy, Xu *et al*. (2016) proposed a self-centering energy dissipation braced system which used friction mechanisms between inner and outer tube members to dissipate energy. Latour *et al*. (2015) carried out an experimental study on five different interfaces which can be employed as dampers in the partial strength Double Split Tee (DST) joints equipped with friction pads. They compared the cyclic behavior of five friction materials and investigated the energy dissipation capacity of DST joint. The results pointed out the high-energy dissipation capacity of the proposed joint without any damage to structural elements. Montuori *et al*. (2016) compared the seismic behavior of a T-sub connection equipped with friction dampers with three traditional connection typologies; extended end-plate, RBS and bolted in MR-Frames using incremental dynamic analysis. They concluded that the T-sub connection with friction pads provides higher interstorey drifts which results in increasing energy dissipation capacity of the connection.

In this paper, the rotational friction damper introduced by Mualla and Beleve (2002) is utilized to study the cyclic behavior of three friction materials through experimental analysis to choose the appropriate friction material for using in the rotational friction damper. The tested friction materials are three types of brake linings including; powder lining, super lining and metal lining. Damper specimens are clamped using high strength bolts and are tested under cyclic loading to investigate the hysteretic behavior and potentialities of the tested materials for dissipating energy due to friction mechanism. The hysteretic behavior of dampers with three brake linings and also tribological properties of brake linings after cyclic loading, are studied based on FEMA-356 (2000) acceptance criteria. Finally, according to the experimental results the powder lining is chosen as the most appropriate brake lining for using in the rotational friction damper.

2. Experimental study

In order to investigate the hysteretic behavior of three brake linings as friction pads, a rotational friction damper proposed by Mualla and Beleve (2002) is utilized. The damper consists of metal plates made of ST-52 steel and circular friction pad discs located between the steel plates (Fig. 1).The combination of steel plates and friction discs improves the frictional surface area. The adjustable preloaded M16 class 10.9 bolts clamp plates and discs firmly to each other. The compression force applied on the friction pads is maintained by these preloaded bolts. Disc spring washers are used to control a constant clamping force. Hardened washers are located between these springs and steel plates to protect steel plates during compression (Mualla and Beleve 2002).

In this research, in order to investigate hysteretic behavior of the damper using different brake linings, the following brake linings are studied experimentally:

- Super lining
- Powder lining
- Metal lining

The above mentioned materials are three brake pads made of special composites. The properties of brake linings according to the results of standard tests performed by manufacturer of linings are shown in Table 1.

Friction dampers are displacement-dependent energy dissipation devices and their sliding force is independent of the earthquake frequency. The friction mechanism is described by Coulomb’s law and the coulomb law is explained through the following equation

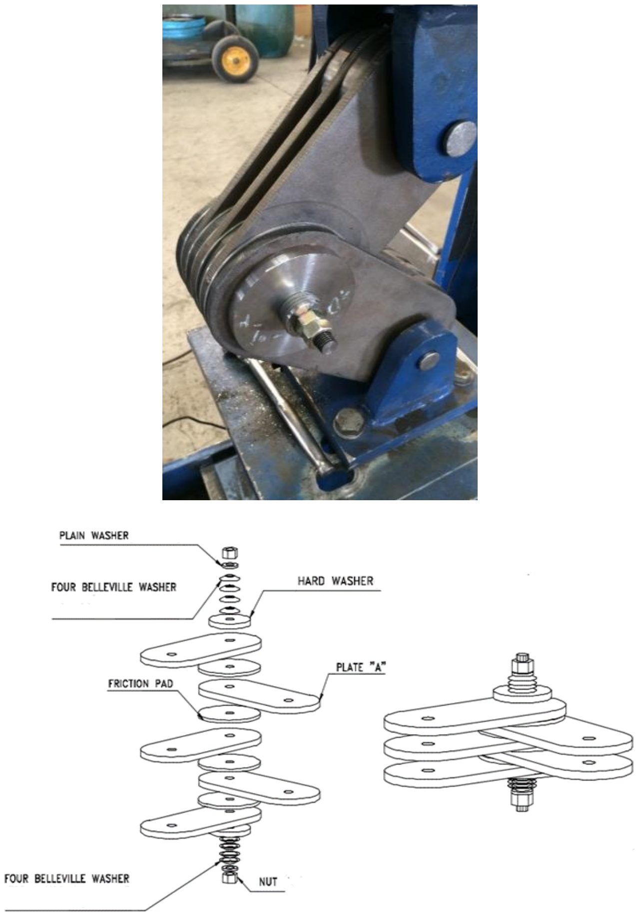


Fig. 1 Friction damper detail

Table 2 Tested Specimens properties

Material	Friction coefficient (sliding)	F(kN)	Torque (N.m)
Super lining on steel	0.437	66	270
Powder lining on steel	0.537	100	300
Metal lining on steel	0.38	70	270

$$F = \mu N \tag{1}$$

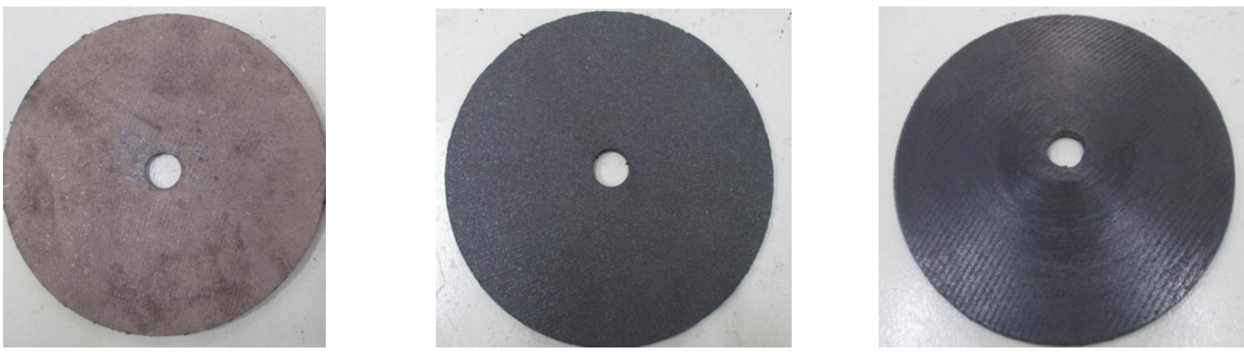
Where F, N and μ represent, the friction force, the surface normal force and friction coefficient, respectively (Fallah and Honarparast 2013). The cyclic behavior of friction damper depends on the friction coefficient and the surface normal force. The friction coefficient strongly depends on the tribological properties of the surface in contact, for example; surface texture, roughness, adhesion. Therefore, the energy dissipation capacity of damper is influenced by friction coefficient (Latour *et al*. 2014).

The friction coefficients of three materials on steel, which studied in this paper are presented in Table 2. The preloaded force (F) and Torque of bolts are also presented in Table.2. The texture of materials are also displayed in Fig. 2.

The damper bolts are tightened with a wrench. Several damper specimens with different friction pads are constructed and the value of tightening torque is measured for each specimen with a torque meter. The tightening torques and preloaded forces of bolts are presented in Table 2.

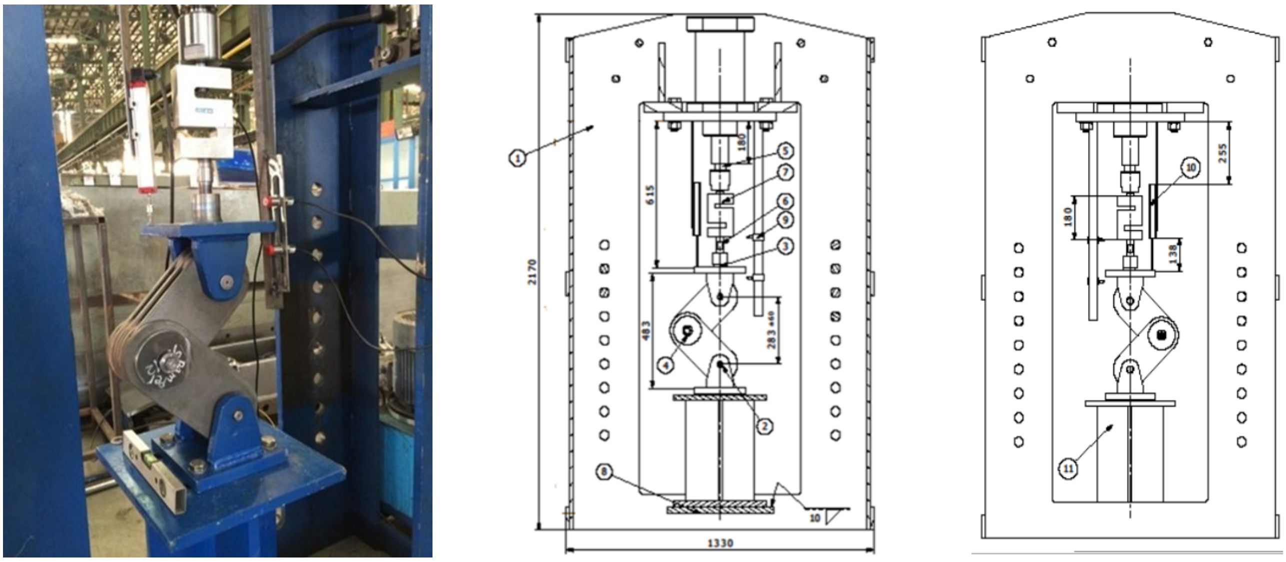
Table 1 Brake linings properties

Tested parameters	Standard reference	Acceptance range	Average result		
			Super lining	Powder lining	Metal lining
Special abrasion	ISIRI -586(2011)	$\leq 3.04e^{-7}$	1.49e-7	1.8e-7	1.31e-7
Density (gr/cm^3)	ISIRI -3100(2012)	≥ 2.2	2.29	2.3	2.7
Effect of heat	ISIRI -586(2011)	No Swelling No Cracking	Ok	Ok	Ok
Appearance situation	ISIRI -586(2011)	No Cracking, No roughness, No fracturing	Ok	Ok	Ok



Super lining Powder lining Metal lining

Fig. 2 Friction pads before experiment



1. Press table
2. Bracket 1
3. Brcaket 2
4. Damper
5. Joint
6. Stod bolts
7. Load cell
8. Plate
9. Microswitch
10. LVDT
11. Stand

Fig. 3 Test setup

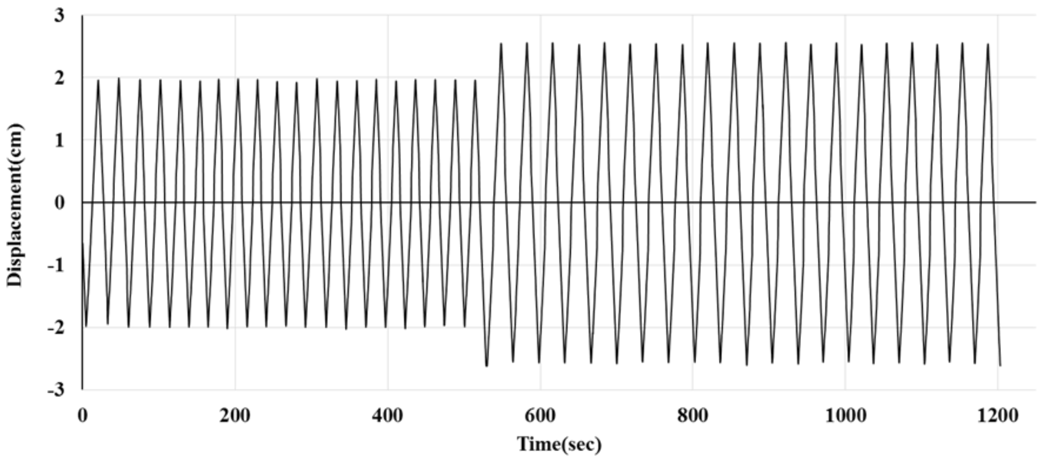


Fig. 4 Displacement loading history

2.1 Test setup and loading protocol

The tests are performed by a 100 kN capacity hydraulic jack. Fig. 3 represents the test setup, in which a load cell and a LVDT are used to measure the load and the displacement, respectively. The damper is tested under a series of displacement controlled cyclic loading in two amplitude according to FEMA-356 (2000) protocols. First, 20 loading cycles with 20 mm amplitude and if the specimen does not fail, another 20 loading cycles with 26 mm Amplitude are applied. The amount of load is measured by load cell and the amount of displacement is measured by LVDT at the end of each loading cycle. The force and displacement histories are recorded by a multi-channel data acquisition device and the force-displacement hysteretic behavior of specimens are plotted. The displacement history is illustrated in Fig. 4. The thickness of friction pads which used in damper is 4 mm.

3. Test results

3.1 Hysteretic behavior

The force-displacement hysteretic curves of all tested specimens are obtained from the experimental analysis. All dampers are tested under cyclic loading protocol discussed by FEMA-356 (2000) up to displacements equal to 2 cm. Fig. 5 represents the obtained curves. According to Fig. 5, all specimens exhibit rigid-plastic hysteretic behaviors. The idealized friction damper should display stable hysteretic loops in desired displacement with minimum strength degradation in 40 cycles. The experiment results represent that in the case of damper with metal lining, as the number of loading cycles increases the load carrying capacity of damper decreases, particularly in initial cycles, due to abrasion of interfaces. Moreover, the results show that damper with powder linings shows stable hysteretic loops and high ductility under cyclic loading in determined displacements. According to the test results, as the number of loading cycle increases the load carrying capacity of the damper with super lining decreases due to corrosion of friction pads especially in initial loading sequences.

3.2 The test result approval

FEMA-356 (2000) proposes some experimental tests to approve the displacement dependent energy dissipation devices and introduces some acceptance criteria for the test results. In this paper, the tests suggested by FEMA-356 (2000) are performed on damper specimens with different friction materials and the results are investigated according to the acceptance criteria which is described below:

(1) The force-displacement response of a displacement-dependent device is a function of the relative displacement between each end of the device. The effective stiffness (k_{eff}) of dampers is calculated for each cycle of deforma-tion as follows (FEMA-356 2000)

$$k_{eff} = \frac{|F^{-}| + |F^{+}|}{|\Delta^{-}| + |\Delta^{+}|} \tag{2}$$

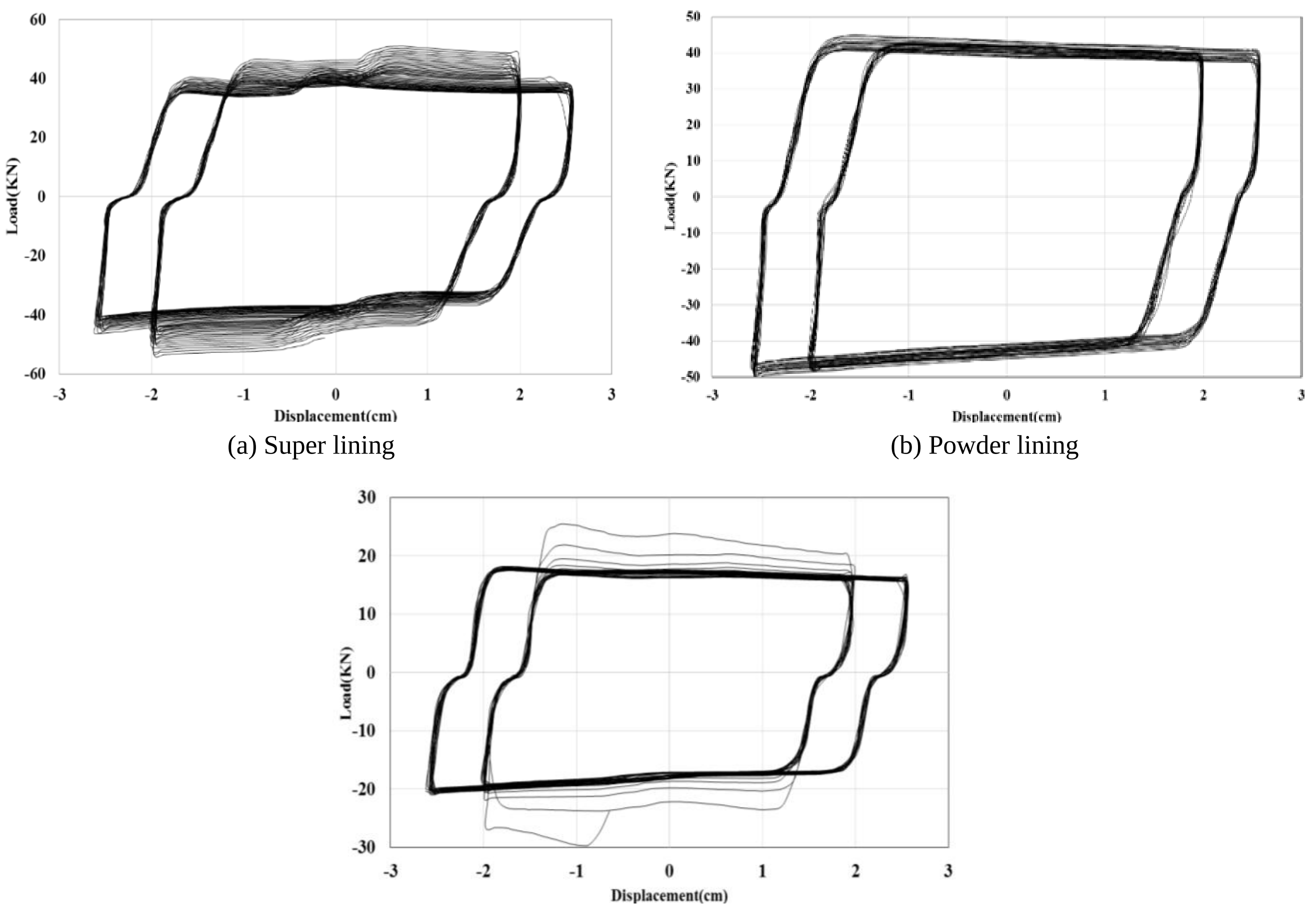
where forces $F^{-}$and$F^{+}$are calculated at displacements Δ^{-} and Δ^{+}, respectively. According to FEMA-356, the effective stiffness (k_{eff}) of dampers for each cycle should not differ more than ±15% from the average effective stiffness calculated from all cycles in the test (FEMA-356 2000).

(2) The equivalent viscous damping of a friction damper (b_{eff}) exhibiting stiffness is calculated for each cycle of deformation as (FEMA-356 2000)

$$b_{eff} = \frac{1}{2\pi}\frac{W_D}{k_{eff}\,\Delta_{ave}^2} \tag{3}$$

where k_{eff} is calculated in Eq. (2), and W_D is the area enclosed by one complete cycle of the force-displacement response of damper during cyclic loading test. Δ_{ave} equal to the average of the values of displacements Δ^{-} and Δ^{+}. The obtained values of b_{eff} should be between $\pm$15% from the average values of b_{eff}.

(3) The amount of energy dissipated by damper during cyclic loading is calculated by evaluating area of the hysteretic loop (W_D) based on FEMA-356. The area of the hysteretic loop at the end of cyclic loading should not differ by more than ±15% from the average area of the 20 test cycles.



(a) Super lining

(b) Powder lining

(c) Metal lining

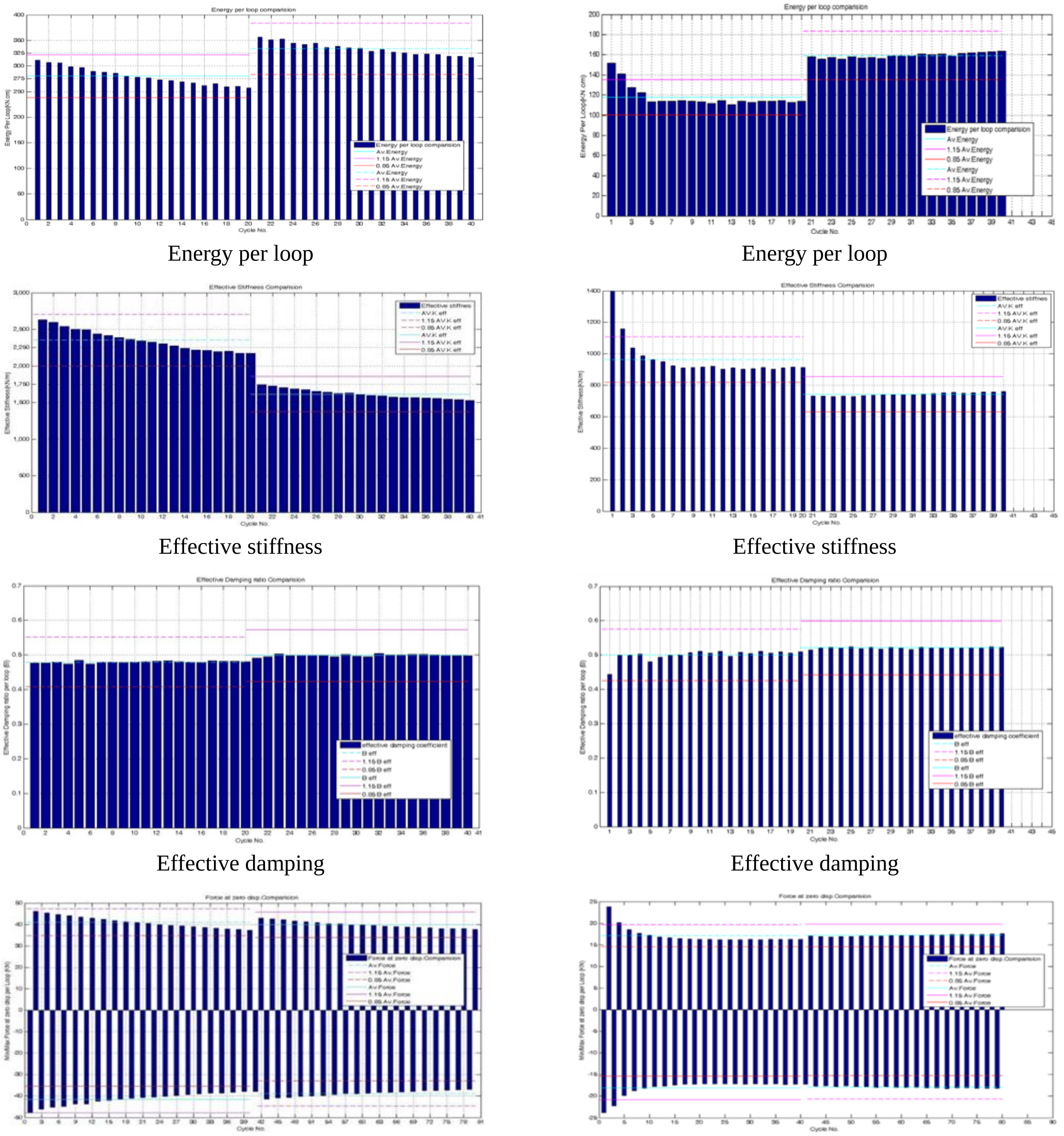
Fig. 5 Hysteretic behavior of dampers with three friction materials

(4) The forces at zero displacements of dampers are calculated and compared with ±15% from the average value, and calculated for all cycles in that test (FEMA-356 2000).

The above mentioned acceptance criteria are studied for all three brake linings and the results are represented in Fig. 6. According to the test results the damper with powder lining and super lining satisfy all approval conditions while in the case of the metal lining some acceptance criteria such as energy per loop, effective stiffness and force at zero displacement are not satisfied.

3.3 Study on friction pads appearance after cyclic test

The appropriate friction material for friction damper should show high abrasion resistance under cyclic loading and the friction pad should have adequate resistance under tension or compression loads and low fragmentation under cyclic loading. Moreover, the loss of friction coefficient should be negligible particularly during first and final



Energy per loop | Energy per loop

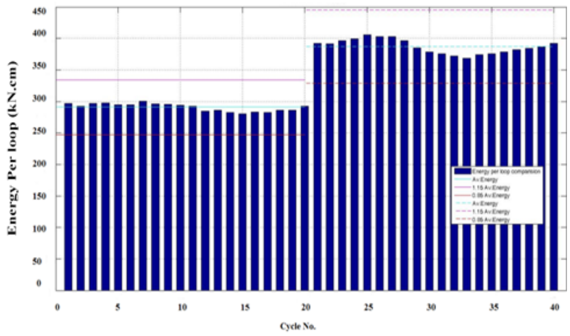
Effective stiffness | Effective stiffness

Effective damping | Effective damping

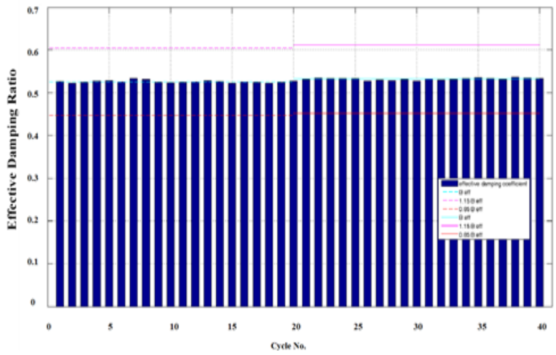
Force at zero displacement | Force at zero displacement

(a) Super lining | (b) Metal lining

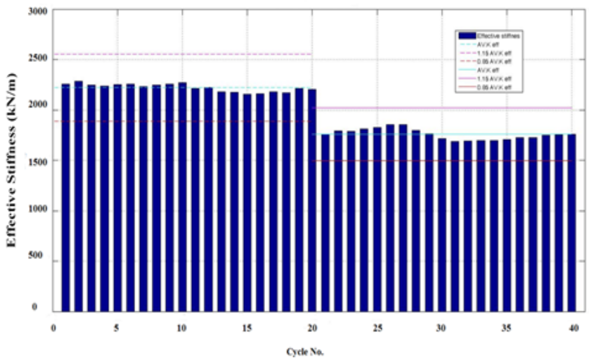
Fig. 6 The test results assessment according to FEM-356 acceptance criteria: (a) super lining; (b) metal lining; (c) powder lining



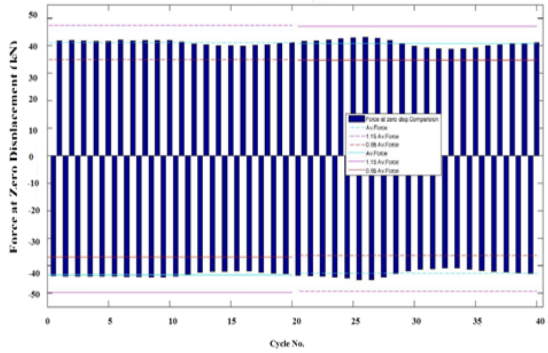
Energy per loop



Effective damping



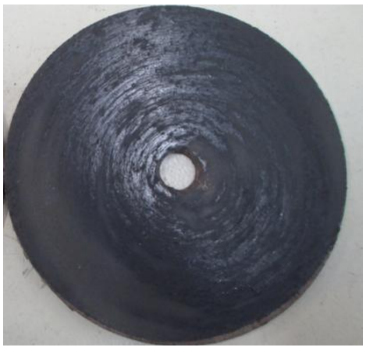
Effective stiffness



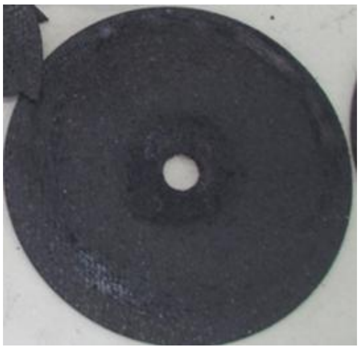
Force at zero displacement

(c) Powder lining

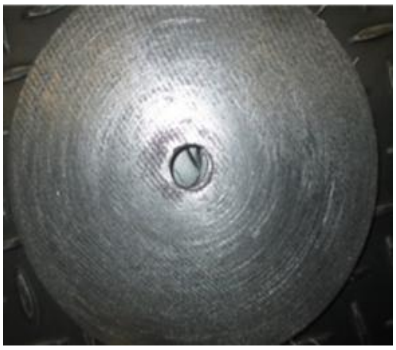
Fig. 6 Continued



Super lining



Powder lining



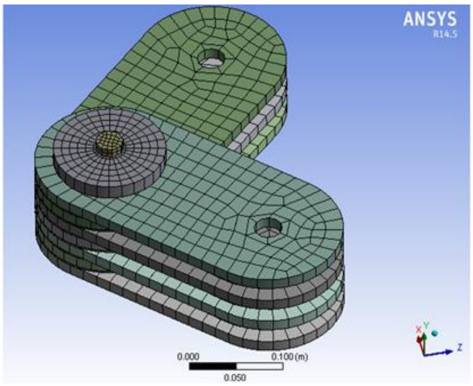
Metal lining

Fig. 7 Friction materials after experiment

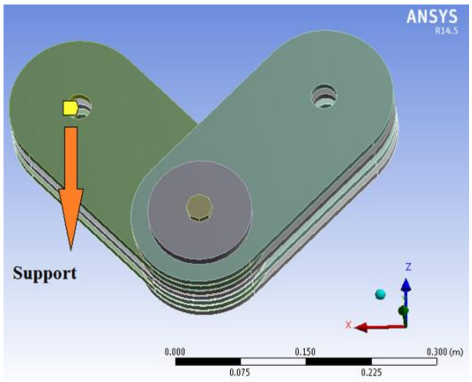
loading cycles. Fig. 7 displays the appearance of brake linings at the end of the tests. According to the Fig. 7 the metal linings show significant abrasion and loss of friction coefficient under cyclic loading. The abrasion of powder lining is negligible at the end of cyclic loading while in the case of super lining the abrasion is extensively high.

4. Numerical modeling

The ANSYS software (2013) is used to perform finite element simulation of the rotational friction damper with powder lining. The SOLID 185 element is used for modeling the damper components. SOLID185 has eight nodes in which each node has three degrees of freedom. This element is capable of modeling plasticity, hyper-elasticity, stress stiffening, creep, large deflection, and large strain (ANSYS 2013). The numerical simulation of the damper needs to present realistic behavior of contact interaction between different parts of the damper. In ASNSY, Surface-surface contact is modeled using TARGET and CONTACT element in which the element with higher stiffness is defined as TARGET element. The friction coefficient is considered 0.537. It is assumed that the bolts are rigidly bonded to the hole to transfer the preloaded force of bolt completely. Since the damper is attached to the beam of the structural frame using steel bolts, it is assumed that the damper is fixed in all transla-

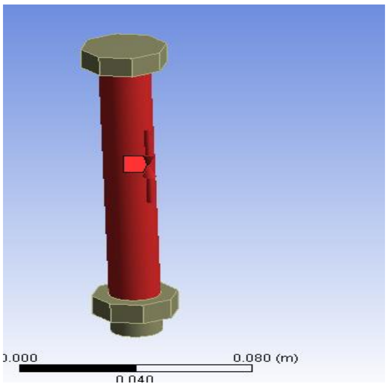


Finite element model

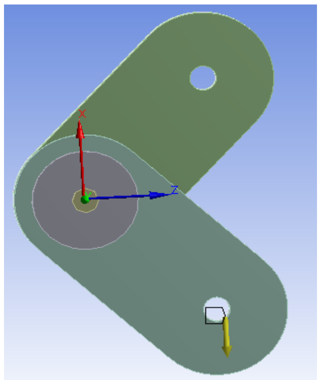


Support definition

Fig. 8 Finite element models and support definition of the damper



Step 1



Step 2

Fig. 9 Damper loading steps in finite element simulation

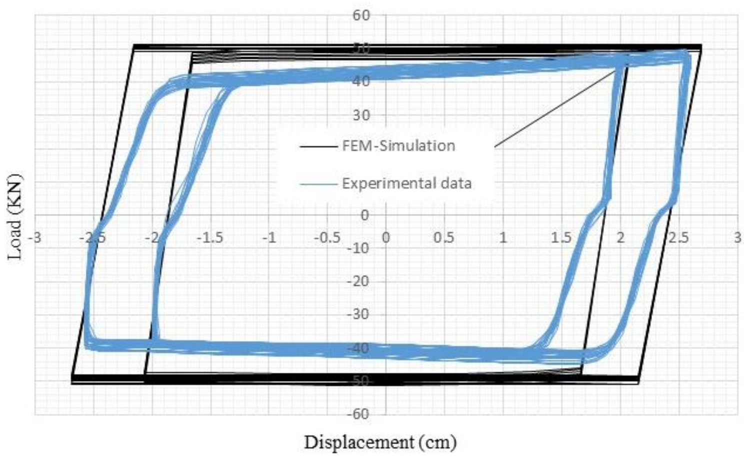
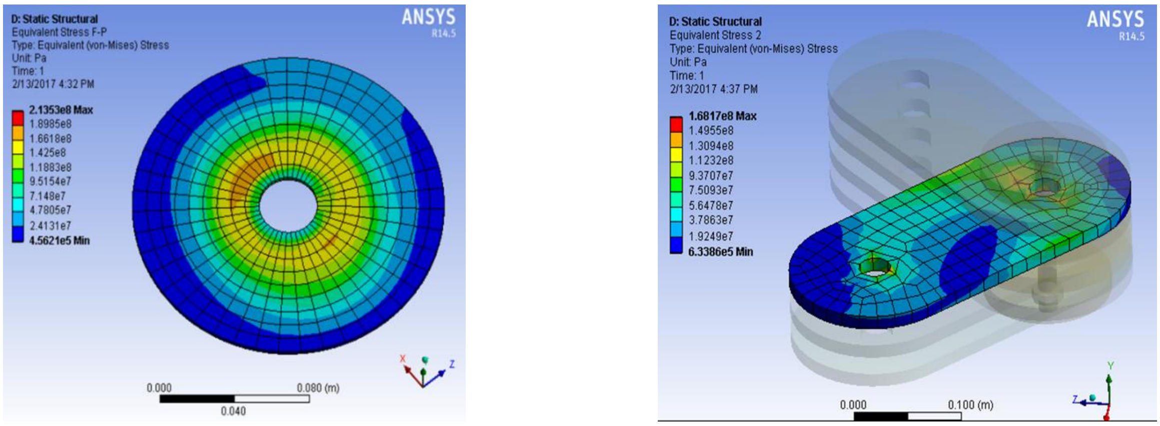


Fig. 10 Comparison of hysteretic behavior of the damper with powder lining in finite element and experiment.

tional direction (*X*, *Y* and *Z*), and it is allowed to rotate freely only in *Y* direction. The material properties of the damper components defined in finite element simulation are exactly identical to experiment. The St-52 steel is used for defining the damper steel plates and washers. The Modulus of elasticity, yield stress and ultimate stress of St-52 are 210 GPa, 360 and 520 MPa, respectively. The finite element model of the damper and the location of supports defined in finite element simulation are shown in Fig. 8.

The loading protocol includes two step (as shown in Fig. 9); first, the preloaded forces of bolts presented in Table 1 are applied on external surface of bolts, following; in order to study the hysteretic behavior of the damper, the cyclic displacement is applied on the surface of the steel plate in the location of bolts. In accordance with FEMA-356 (2000) loading protocol, the displacement controlled cyclic loading is applied in two amplitudes similar to experimental program (First, 20 loading cycles with 20 mm amplitude



Stress contours in washers — Stress contours in friction pad and steel plates

Fig. 11 Von-Misses stress contours in the damper components

and if the specimen does not fail, another 20 loading cycles with 26 mm amplitude are applied) and the force-displacement hysteretic curve of the damper with powder lining is obtained.

Fig. 10 compares the hysteretic behavior of the damper with powder lining in finite element simulation to experiment. As it is observed, there is a good agreement between finite element and experiment results in both loading amplitudes. Moreover, the Von-Misses stress contours in steel plates of the damper and washers are shown in Fig. 11. It is seen that the values of Von-Misses stress is in the elastic region and no plastic behavior is observed under cyclic loading.

5. Conclusions

In this paper, an experimental program is performed to select the most appropriate friction materials for using in the rotational friction damper. Therefore, three brake linings include; powder lining, super lining and metal lining are tested under cyclic loading according to FEMA-356 (2000) loading protocols. The test results are studied according to acceptance criteria presented by FEMA-356. Moreover, the tribilogical properties of brake linings are studied at the end of cyclic test. According to the experimental analysis following results are obtained:

- The damper with powder lining exhibits more stable hysteretic behavior and low strength degradation in comparison to the others. Moreover, the enclosed area by hysteretic diagram of the damper with powder linings is larger than the other damper specimens. Therefore, the energy dissipation capacity of damper with powder linings is more than the others.
- The metal and super linings abrasion at the end of cyclic loading are extensively high while powder linings show low abrasion under cyclic loading compared to the other tested friction materials.
- The powder linings and super lining meet the approval conditions for passive energy dissipation devices described by FEMA-356, while in the case of the metal lining some acceptance criteria are not satisfied.
- According to the experiment results and FEMA-356 acceptance criteria, it can be concluded that the powder lining is the most suitable lining to be employed as friction pad in the rotational friction damper.
- In addition to experiment, the damper with powder lining is modeled in ANSYS software (2013) and cyclic behavior of the rotational friction damper with powder lining in finite element simulation and experiment is compared. A good agreement is observed between finite element and experiment results, therefore this model can be used for numerical simulation and design of rotational friction damper. Moreover, the steel plates and washers of the rotational friction damper showed elastic behavior under cyclic loading.

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