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OVERVIEW OF RECENT PROJECTS IMPLEMENTING ROTATIONAL FRICTION DAMPERS

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Abstract

A novel damper device based on the rotational friction hinge concept invented by the first author is described. The testing of steel structure with rotational friction dampers (RFDs) at a large-scale shake-table testing facility demonstrated the remarkable efficiency of the damping system for reducing the lateral displacements and interstory drifts. The initial T-shape configuration of the RFD has been further improved over the years. Commercial supply of RFDs with broad range of slip capacities is now provided by Damptech based in Denmark.

The conventional seismic protective systems with friction dampers typically include chevron- or v-braces, but RFDs can be also implemented as component of base isolation systems. The paper presents several essential projects in different countries which demonstrate the worldwide acceptance of the RFD concept and form the basis for further research and development activities. Some of the presented damper applications are in new buildings, while others are designed for seismic upgrade of existing structures.

Keywords: earthquake protection, friction damper, passive energy dissipation.

Introduction

Originating from the 70's of the last century, the capacity design concept has now become a worldwide-accepted approach in earthquake-resistant design. It assumes that the structural system must be made as insensitive as possible to the strongly-variable and difficult-to-predict characteristics of seismic actions. This can be achieved only if the structural engineer introduces a hierarchy in the resistances of the structural members in a way which results in a well-predictable and ductile seismic performance. The capacity design concept is also named "failure mode control" implying that the designer must provide favorable pattern of plastic (dissipative) zones which does not endanger the overall safety of the building/facility. It is also recognized that even the structures made of very ductile materials, such as structural steel, have "brittle" components which must be protected from overstressing through providing extra-strength. In moment-resisting frames, this concept resulted in a design strategy called "strong-columns-weak-beams", implying that the ductile frame beams must be purposely made weaker than the frame columns in order to avoid formation of "weak" storey and/or total collapse initiated by premature column failure.

Based on the vast experience and lessons learnt from many major earthquakes it became clear, that the conventional structures relying on their ductile response could really survive and save human lives, but in general they failed to limit the extent of damage, which resulted in heavy financial losses and business interruption. In this connection, the development of the structural fuse concept (SFC) can be viewed upon a further step in the evolution of the capacity design philosophy.

Passive energy dissipation devices have been successfully used to effectively protect buildings and structures against earthquakes and storms. The primary reason for introducing energy dissipation devices into a building frame is to reduce the dynamic response and damage of the frame.

This paper presents the development, testing and application of a novel, worldwide patented friction damper system developed by 1st author in order to control the vibration in structures and buildings due to earthquakes and/or strong winds. The capability of the dampers to dissipate energy has been extensively studied and tested in previous research programs both experimentally and numerically, as well as in several finalized projects. Friction damper devices have been used in many buildings and structures around the world because they provide high-energy dissipation potential at a relatively low cost while being easy to maintain.

The dampers described in this paper are patented property of Damptech. The dampers are mainly used for vibration control of structures and base isolation of structures and are based on a unique rotational friction concept. So far Damptech dampers have been installed in many projects around the World, including the tallest building in Japan.

1. Description of Rotational Friction Damper Devices

The rotational friction damper (RFD) consists of several types of steel plates pre-stressed together by a steel bolt to form a 2, 4, 6 or 8 joint shape illustrated in Figure 1A-B and hence the name 4J-Damper. Between the steel plates there are circular friction pad discs made of high-tech composite material. In order to have constant pre-stressing force several disc springs are used. Between these springs and the two external steel plates hardened washers are placed so that a uniformly distributed pressure can be achieved. The energy absorbing potential of the device can be easily increased by adding more layers of steel plates and friction pads.

Figure 1A - Damptech 4J -damper model

Figure 1B - Multi-joint large-capacity RFDs

A possible configuration of the device in a frame structure can be seen in Figure 2. The long plates are connected to the connection in the girder by a pin. In order to activate the energy absorbing mechanism of the device the other ends of damper plates are connected to the steel bracing members.

When the structure is vibrating the friction hinge is loaded in torsion. The friction at interface between the composite material and the steel plates resist the torsion with a sliding moment M_s, thus a portion of the induced energy is dissipated when there is a rotation in the frictional hinge. The resistance due to the device hinders the lateral movement of the storeys. Consequently, if no further energy is induced, the vibration of the frame structure becomes smaller and smaller with each relative rotation between the steel plates. With the pre-stressing force of the bolt and the arrangement of the damper devices in the structure the degree of the resistance of the relative rotation at the device can be controlled. The simple mechanism allows an easy handling and installation.

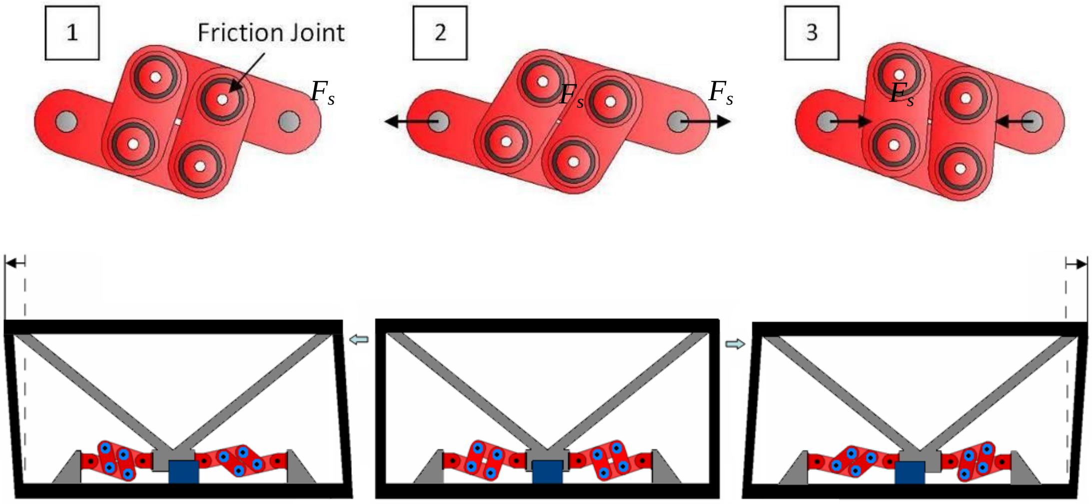

Figure 2 - Left: Frame structure moved to the left. Middle: Frame structure in initial position. Right: Frame structure moved to the right

1.1 Features of RFDs

The friction dampers are classified as displacement dependent devices and the features of the friction dampers are:

- For a given slip force (F_S) and displacement (Δ) in a damper, the energy dissipation of a friction damper is greater than those of other damping devices (Figure 4).
- The dampers are not active during low velocity wind and service loads.
- The dampers do not contain any liquids so they cannot have any leakage and therefore they do not need to be inspected regularly, thus, maintenance requirements are very low.
- The damper sliding moment M_s is independent on velocity.
- The damper sliding moment M_s is independent temperature.

2. Shake-table tests of three-storey frame

In 2001, an international team conducted intensive research program on a three-storey building equipped with RFDs at the advanced large-scale shake-table testing facility of the NCREE in Taiwan. The test building was a steel moment-resisting frame structure with 3.0 m story height and 4.5 m bay width in the direction of shaking (Figure 3).

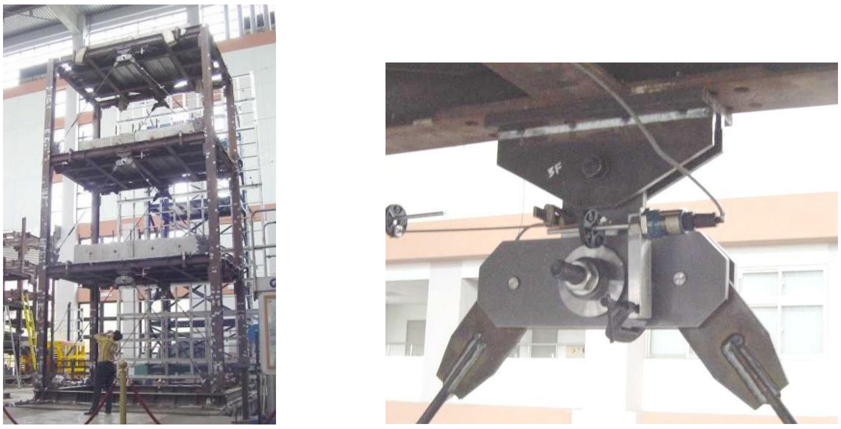

Figure 3 - Layout of full-scale testing at NCREE and closer view of one of the RFDs

The performance of the damped structure was evaluated for 14 cases of seismic input with peak ground acceleration (PGA) from 0.05g to 0.30g. Several patterns of the damper slip resistances along the height of the building were used but each of them was kept for a couple of tests of different intensity. For example, the Kobe Takatori record was first applied with PGA = 0.1g followed by consecutive shaking with PGA of 0.05g, 0.15g and 0.175g, respectively without readjusting the bolt clamping forces and device slip capacities. The other tests with stronger ground shaking (PGA = 0.15g - 0.30g) demonstrated the remarkable efficiency of the damping system in reducing the lateral displacements and interstory drifts of the test building by 70 to 80 %. More detailed information on the testing carried out in NCREE and its results can be found in [1,2].

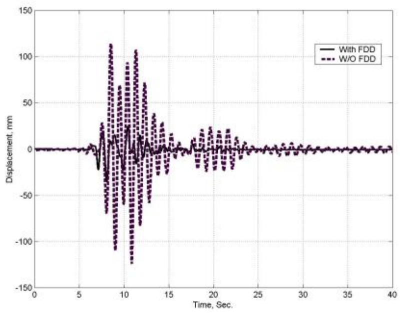

Figure 4- Roof displacement time-histories using Kobe Earthquake with 0.175g PGA

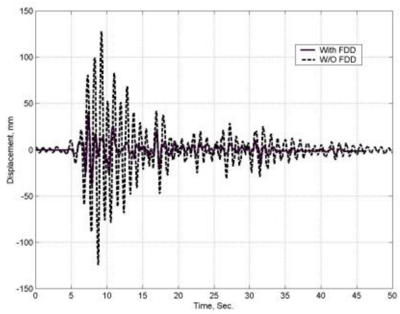

Figure 5- Roof displacement time-histories using El Centro Earthquake with 0.20g PGA

2.1 Equivalent Viscous Damping

It is possible to estimate the equivalent viscous damping ratio of a single degree of freedom system with friction dampers subjected to sinusoidal loading, Mualla et al. [2001]. However, the equivalent viscous damping ratio depends on the amplitude of the sinusoidal load.

If the amplitude of the load is very low, then the dampers will not activate and there will be no increase of equivalent viscous damping by using the dampers.

If the amplitude of the load is moderate or high (compared to the damper capacity), then the dampers are activated and dissipating kinetic energy into thermal energy. In this case the dampers will increase the equivalent viscous damping ratio of the system.

The two phases of damper deformation are the sticking and sliding phases. The frictional moment M_f limits the moment in the frictional hinge. This type of friction damper is defined by a slip load, F_s, an elastic stiffness, K_{bd}, and a ductility ratio, $\mu_d=D_u/D_{yd}$, where D_u and D_{yd} are the ultimate and yield displacements of the RFD, respectively. Energy dissipation *ED* per cycle in the frictional hinge can be written approximately as

$$ED = 4K_{bd}D_{yd}\left(D_u - D_{yd}\right) \quad (1)$$

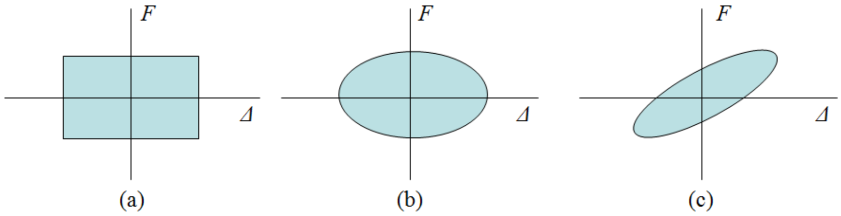

Figure 4 - Comparison of hysteresis loops of different dampers
(a) Friction damper; (b) Viscous damper; (c) Viscoelastic damper

Structure and RFD act in parallel and can be described as a dual system. For a system with a single degree of freedom and assuming that basic system remains elastic, the equivalent viscous damping ratio is obtained by

$$\zeta_{eq} = \frac{2FR\left(SR-FR\right)}{\pi\left(SR+FR^2\right)},\ \frac{FR}{SR}<1 \quad (2)$$

Where, *FR* is the ratio of the total structure force F_{hf} exhibited by the structure, to the damper yield force F_s. And *SR* is the ratio of damper stiffness K_{bd} to the total structure stiffness K_s:

$$FR = \frac{F_{hf}}{F_s} \quad (3) \qquad SR = \frac{K_{bd}}{K_s} \quad (4)$$

The total structure force F_{hf} exhibited by the structure depends on the amplitude of the sinusoidal load and therefore *FR* and also the equivalent viscous damping ratio ζ_{eq} depend on the amplitude of the sinusoidal load.

This formulation is well suited for making a first order estimate of the required damper properties for the design. The relation for ζ can be used to generate a family of curves as a function of *FR* and *SR* as shown in Figure 5.

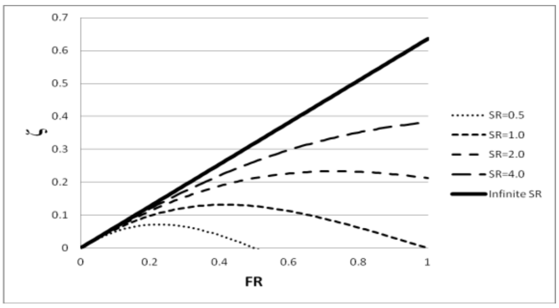

Figure 5 - Equivalent viscous damping for dual system

3. Some of the projects with RFDs dampers

The first application of the friction damper devices in a real building was in two old temple buildings in Japan. The dampers are of the T-Damper model type.

Both temples were soft storey buildings because of the 1st storey which had low stiffness compared to the rest of the building. By adding dampers and bracings at the 1st storey the stiffness of the 1st storey was increased while additional damping was added by the dampers.

The first temple to have Damptech dampers was the Yagurji Temple, which can be seen in Figure 6 below.

An example of the T-Dampers with bracings, that are installed in the temple can be seen in Figure 6.

Figure 6 – Dampers with bracings installed in Yagutji Temple

Another project was a retrofit project in Greece where 2 new floors were added to an existing RC apartment building in Athens. The dampers used for this project are V-dampers and 2-joint dampers, see Figure 7.

Figure 7 – Greece retrofit project

One of the damper models developed by Damptech is a Scissor Damper. The main advantage of this model is that it is capable of very large displacements.

The first application for Scissor Dampers was for a industrial building in Greece, see Figure 8. Since the completion of the project, several earthquakes have hit the region. The most significant were in June 2008 (M 6.5) and in August 07, 2011 (M 4.7) and August 20, 2011 (M4.9). The dampers have performed very well and no excessive displacements or effects of high forces have been observed in the structure.

Figure 8 – Scissor Dampers in Industrial plant in Greece

Also in Greece RFDs with different capacities are used in 2 new office buildings, see Figure 109.

Figure 9 – Two New office building in Greece

4. RFDs for Base Isolation

Damptech dampers have been used in several base isolated buildings in Japan. Base Isolation is a technique for protecting buildings and structures against earthquakes. Basically the entire building stands on rubber bearings that are stiff in the vertical direction but soft in the horizontal plane (low shear stiffness). In the event of an earthquake the ground starts to shake back and forth but because of the low shear stiffness of the rubber bearings the building remains almost stationary even though the relative displacement between building and the ground can be much larger than for a building without a base isolation system.

The dampers further lower the response of the building and ensure that the kinetic energy in the building is dissipated much quicker. The first project where Damptech dampers where used in base isolation was for a 5 storey laboratory building in Japan. For this project base isolation friction dampers with high displacement capacity was used and tested at the Technical University of Denmark in a 250 kN Instron dynamic testing machine. For base Isolation the displacement requirements of the dampers can be very large and the dampers are designed for a maximum displacement of +/- 600 mm.

The damper have a very stable performance and with no decrease in performance over 100 cycles, Nielsen et al. [2004,2] , see Figure 10. This good performance is owing to the use of a special friction pad material between the damper plates in the frictional hinge.

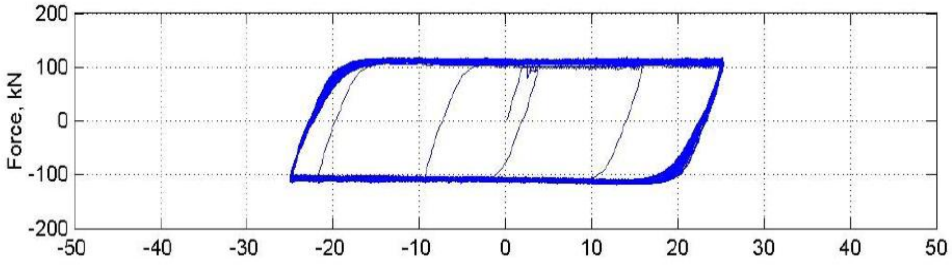

Figure 10 – 100 cycle test of base isolation damper

Figure 11 - a: 5 Story Laboratory building. b: Damper installed at the base of the building

Since the 5 story laboratory project several base isolated buildings of similar size have been equipped with Damptech dampers.

Two other projects with Damptech dampers can be seen in Figure 12. One of them is a 12 story apartment building in Tokyo (Figure 12 - Left) and the other is a 7 story laboratory building in Yokohama (Figure 12 - Right).

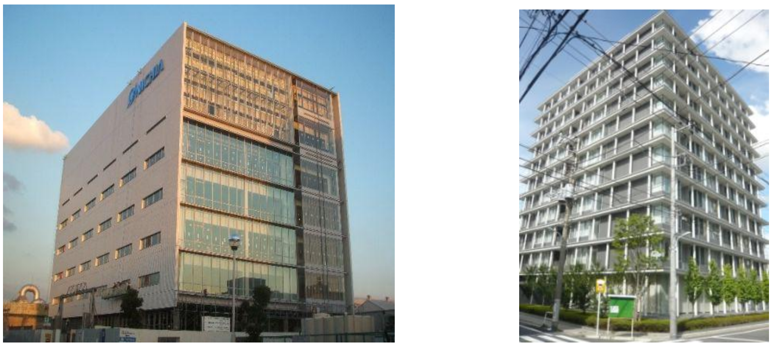

Figure 12 – (Left) 12 story apartment building in Tokyo. (Right) 7 story laboratory building in Yokohama

5. RFDs for base isolation for high-rise buildings

After the success of using the base isolation dampers for medium-rise buildings, it was decided to use the base isolation dampers in high-rise buildings also.

The first high-rise building to be equipped with Damptech dampers in base isolation configuration is a 144 tower in Osaka. The tower is a residential tower with 44 floors and 2 pent house floors. (46 in total)

Other projects with Damptech dampers in base isolation configuration for high-rise buildings are three similar residential towers with 40 floors. Each tower is equipped with many base isolation dampers

Figure 13 - Three residential towers with RFDs   Figure 14 – Dampers installed in residential tower in Osaka, Japan

6. RFDs for Tallest Building in Japan

Takenaka Corp., one of the top 5 construction companies in Japan, is currently building the tallest building in Japan with a height of 300 m. The project is called the "Abeno Harukas" building and will be used for department stores, hotel, museum and more Figure 15.

Because the building is located in Osaka, an area with high seismic activity, it was decided to equip the building with Damptech friction dampers to reduce the demand on the primary structural elements in the event of an earthquake. All dampers have already been installed in the building.

Figure 15 - Abeno Harukas October 2012 (under construction)

Figure 16 - 2250 kN Dampers installed in the tallest building in Japan

The dampers used for the Abeno Harukas projects are unidirectional in the sense that a force F_s is required to activate the dampers, see Figure 16. The dampers in question has 4 friction joints and several layers of steel plates and friction pads to have a large damper capacity of 1500- 2250 kN .

7. V-Bracing Configuration with RFDs

The dampers have been installed in V-Bracings through the height of the 300 m building.

When the top of the frame structure is moved to the left the left damper is compressed while the right damper is in tension and both dampers dissipate energy. Similarly when the top of the frame structure is displaced to the right the right damper is compressed while the left damper is in tension and the dampers dissipate energy see Figure 2. The mechanism of each individual damper can be seen in Figure 2.

During an earthquake the top story of a frame structure in a building as the one in Figure 2 will be moved from left to right repeatedly while the dampers are dissipating the kinetic energy from the earthquake into heat, effectively reducing the response of the structure from the earthquake.

8. EXPERIMENTAL TEST PROGRAM

As a part of the Abeno Harukas Prjoect a large number of experiments for 1500-5000 kN dampers where been conducted at the Technical University of Denmark and testing facilities in Japan. The parameters examined are velocity dependence, displacement amplitude dependence, many loading cycles tests and etc..

1500-2250 kN Damper Tests

The tests for the 1500 kN damper was performed with a 3 MN dynamic servo testing machine at testing facilities in Japan, Mualla et al. [2012]. The test setup can be seen in Figure 17.

Figure 17 - Test setup of 1500 kN damper in testing facilities in Japan

5000 kN Damper Tests

Tests of a 5000 kN dampers where tested at testing facilities at the Technical University of Denmark. The damper was tested in a Instron machine with 5000 kN capacity in dynamic tests, Mualla et al. [2010].

The test setup can be seen in Figure 18.

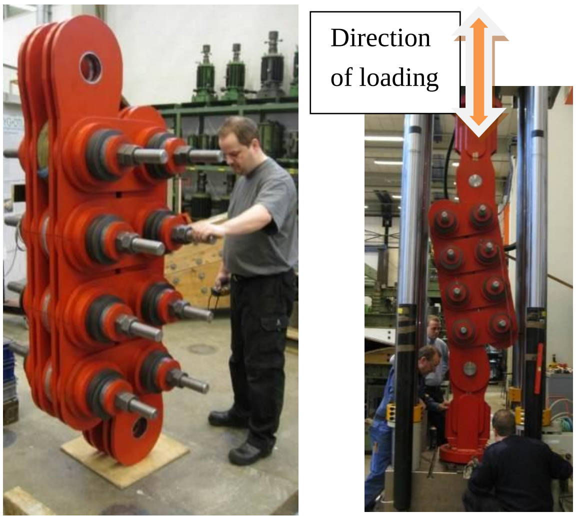

Figure 18 - 5000 kN Damper Tests at the Technical University of Denmark

Some of the building projects in Japan where Damptech dampers have been installed can be seen in Figure 19 below.

Figure 19 - Some Damptech projects in Japan (including tallest building in Japan)

RFDs are used in other projects around the world. Figure 20 showing the installed dampers in large hospital project in Iran with 800 beds.

Figure 20 - Dampers installed in large hospital project.

First project in Chile

In Chile RFDs are used in a 19 floors new building. Figure 21 shows the installed dampers in diagonal bracing system where different sizes and capacities are used.

Figure 21 - Dampers installed in diagonal bracing system.

9. Seismic retrofit of precast RC structures

Passive energy dissipation systems and devices can be successfully used for seismic upgrade of single-storey buildings with precast RC structure. Typical problems associated with this structural system are its relatively low lateral stiffness, low inherent damping, low structural redundancy and connections between primary structural members which are not suitable for seismic areas. The set of these drawbacks often results in severe damage in strong ground shaking. A study made in Turkey has revealed that the majority of the existing buildings of this type (industrial single-storey precast RC frame structures) are highly vulnerable to seismic actions and very few of them satisfy the provisions of current Turkish design code. An example of seismic retrofit of such building with V-shaped rotational friction dampers is shown in Figure 22. The major advantage of this approach is the fact that it was implemented without any business interruption of the building.

Figure 22 – V-shaped rotational friction dampers on precast RC structure

Conclusion

A number of damping systems have been presented and discussed. These systems are very effective in damping vibration in buildings and structures. The damping systems are based on a unique rotational friction concept that has worldwide patents. The dampers have been successfully used in many projects around the world including the tallest building in Japan.

The devices can be used to efficiently protect building against earthquakes, storms and can also be used for reducing machine vibration. The devices are flexible and available in many different models that each have their own advantage for certain applications.

These damping systems & dampers were used in 8 countries around the world including Chile.

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